# REDEFINING RADAR – CAMERA SENSOR FUSION: A LEAP TOWARDS AUTONOMOUS DRIVING WITHOUT LIDAR

Autosens Brussels 2023


Dr. Andras Palffy

PERCIVAI

Co-founder

AI for radars

andras.palffy@perciv.ai



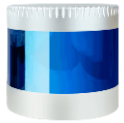

TU Delft

Post-doc researcher

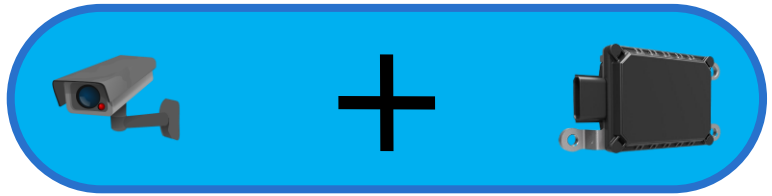
Microwave Sensing, Signals and Systems Group

Intelligent Vehicles Group

# Typical sensors

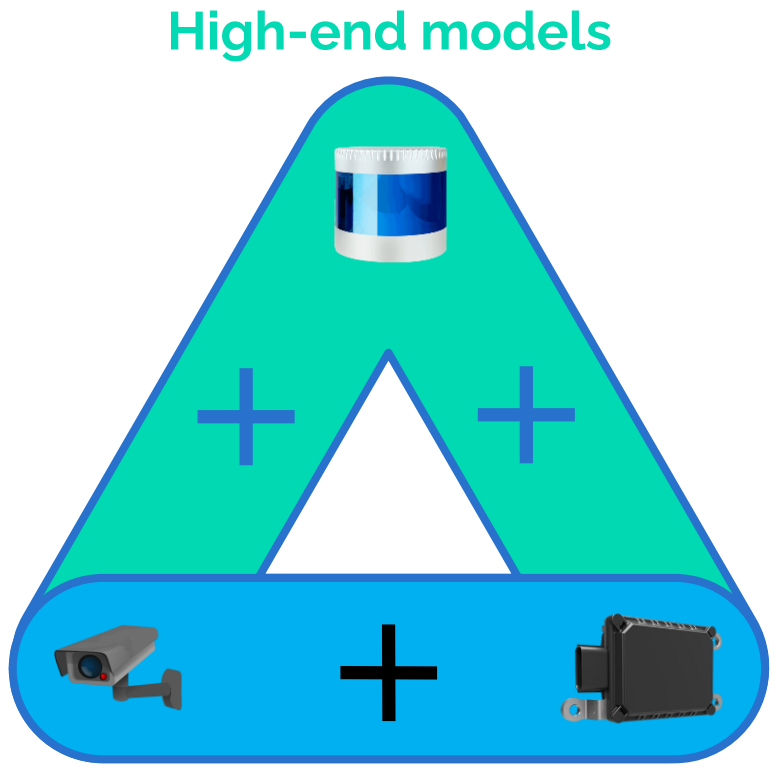
| |  |  |  |
|---|---|---|---|
| 3D | ✗ | ✓ | ✓ |
|  | ✗ | ✗ | ✓ |
|  | $ | $$$ | $ |

| |  |  |  |
|---|---|---|---|
| 3D | ✗ | ✓ | ✓ |
|  | ✗ | ✗ | ✓ |
|  | $ | $$$ | $ |



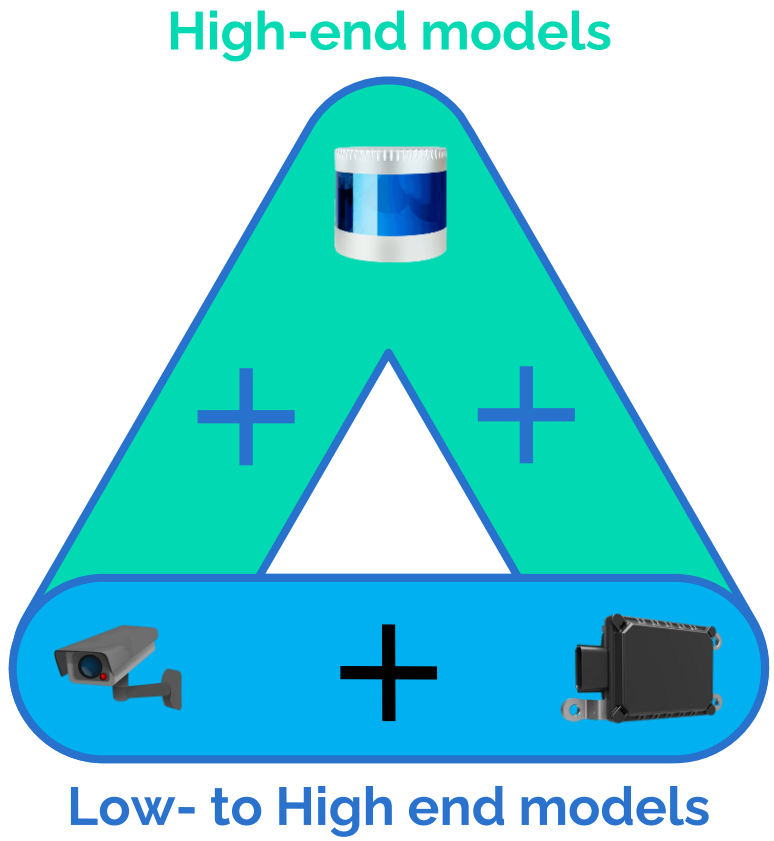
**Low- to High end models**

| | | | |
|---|---|---|---|
| 3D | ✗ | ✓ | ✓ |
| | ✗ | ✗ | ✓ |
| | $ | $$$ | $ |



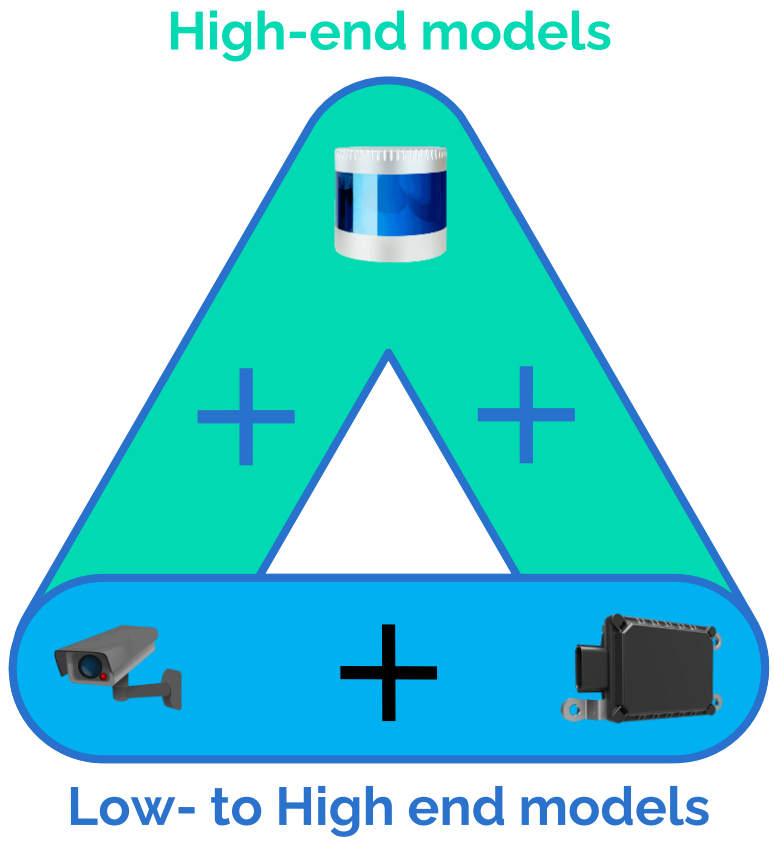
# Radars are here to stay

| |  |  |  |
|---|---|---|---|
| 3D | ✗ | ✓ | ✓ |
| | ✗ | ✗ | ✓ |
| | $ | $$$ | $ |



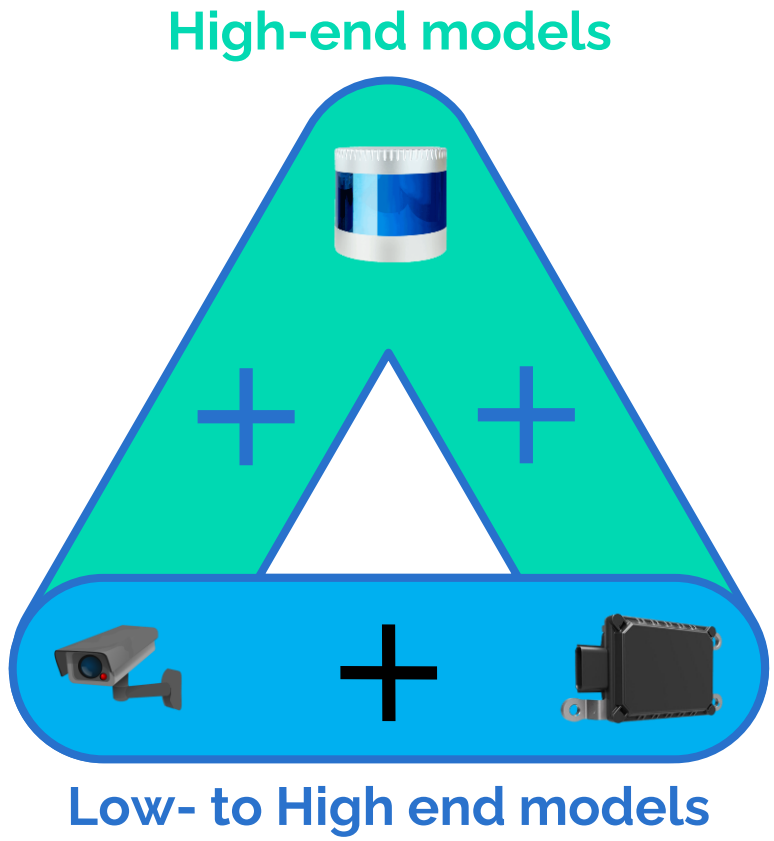
# Radars are here to stay

| |  |  |  |
|---|---|---|---|
| 3D | ✗ | ✓ | ✓ |
|  | ✗ | ✗ | ✓ |
|  | $ | $$$ | $ |
| AI | ✓ | ✓ | ✗ |



# Radars are here to stay, but need AI to be a true alternative.

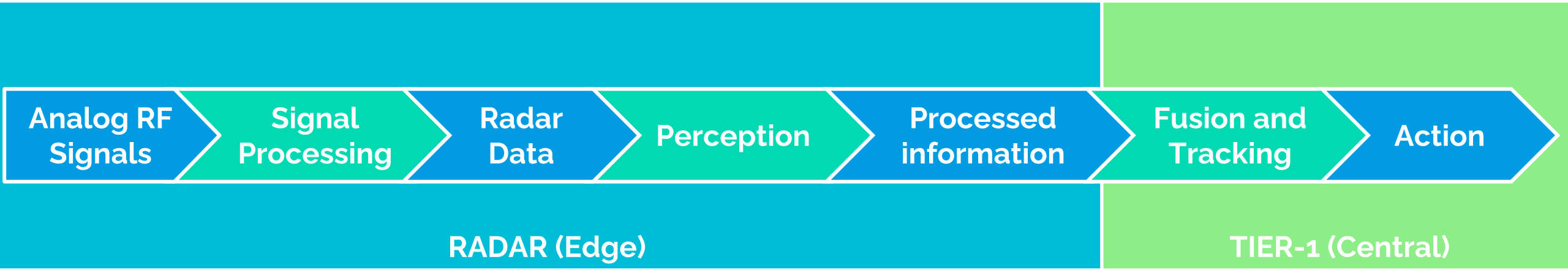
| |  |  |  |
|---|---|---|---|
| 3D | ✗ | ✓ | ✓ |
|  | ✗ | ✗ | ✓ |
|  | $ | $$$ | $ |
| AI | ✓ | ✓ | ✗ |



# AI-driven radar is a must.
# Delivering it first is a win.

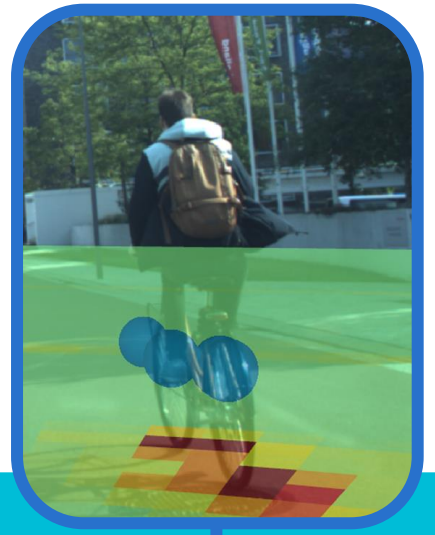

PERCIVAI

# Today's Radar Perception




PERCIVAI

# Today's Radar Perception



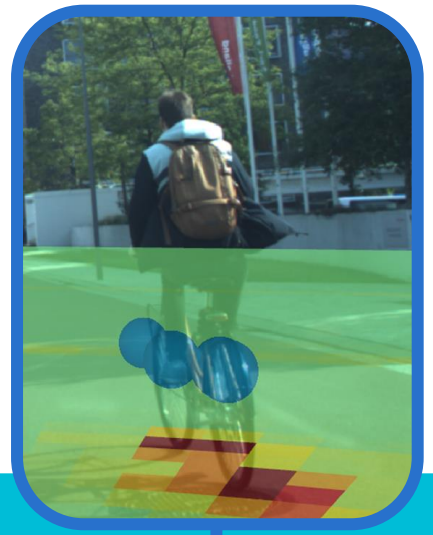
Analog RF Signals → Signal Processing → Radar Data → Perception → Processed information → Fusion and Tracking → Action

RADAR (Edge)

TIER-1 (Central)

PERCIVAI

# Today's Radar Perception



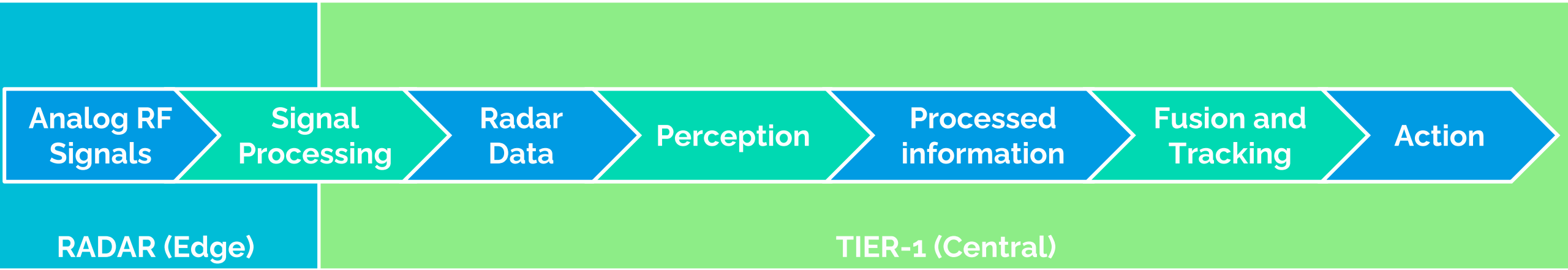
Analog RF Signals → Signal Processing → Radar Data → Perception → Processed information → Fusion and Tracking → Action

RADAR (Edge)

TIER-1 (Central)

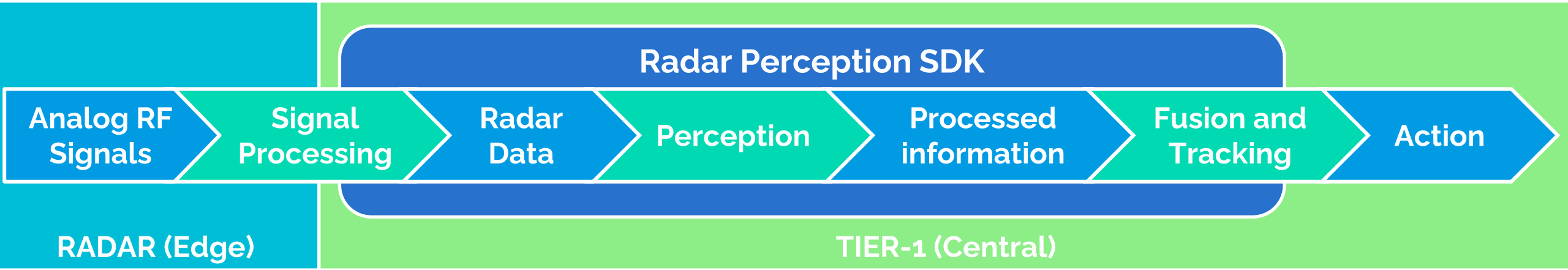
PERCIVAI

# Next-Gen Radar Perception




PERCIVAI

# Next-Gen Radar Perception

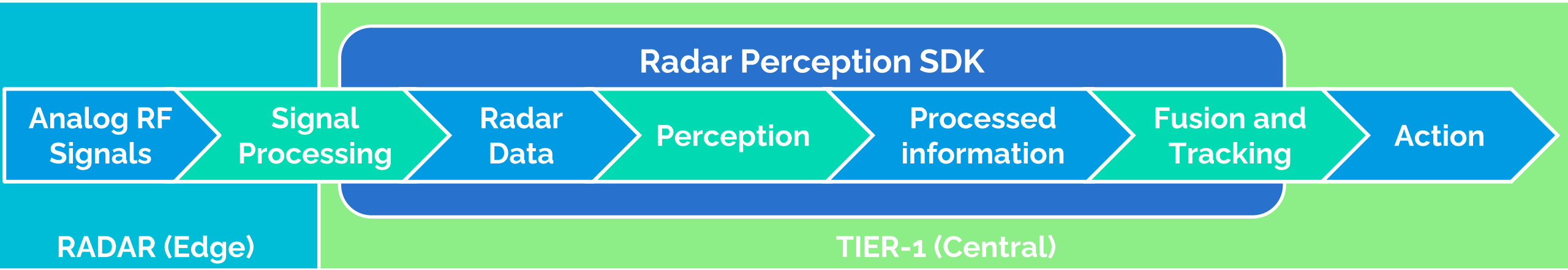



PERCIVAI

# Next-Gen Radar Perception

**SDK**

**Software defined**



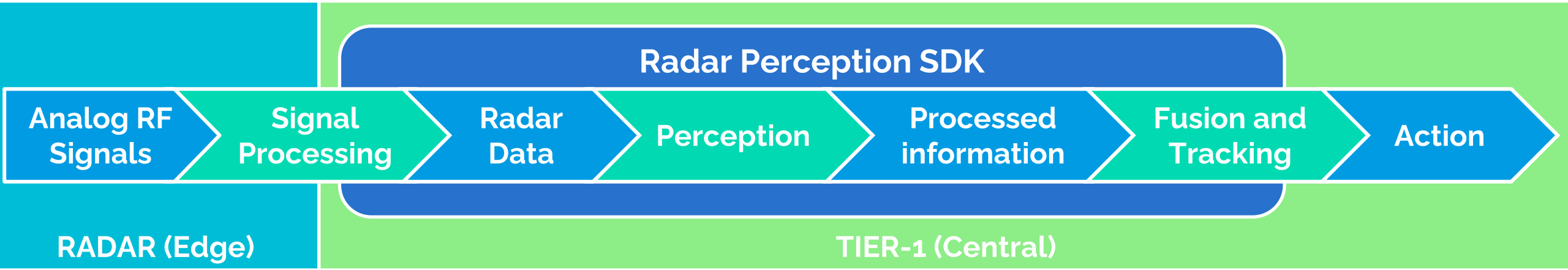

PERCIVAI

# Next-Gen Radar Perception

SDK

**Software defined**

**AI Driven**




PERCIVAI

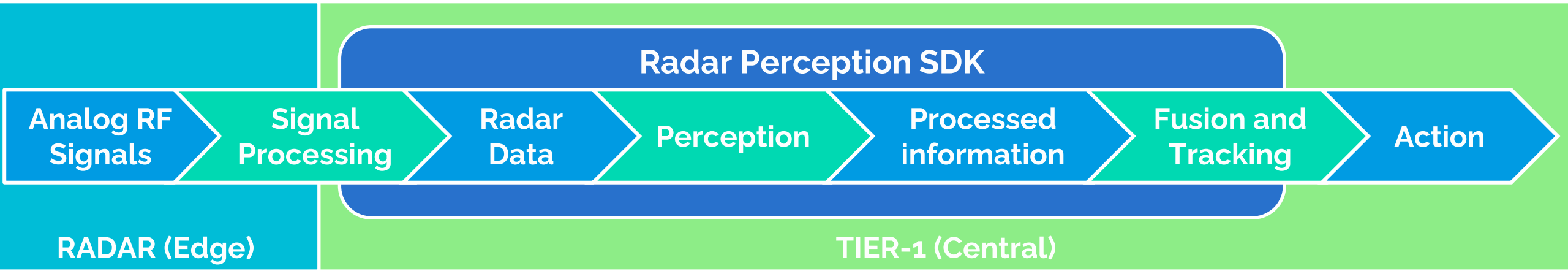
# Next-Gen Radar Perception

SDK

**Software defined**

**AI Driven**

**Hardware agnostic**




PERCIVAI

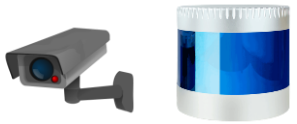
# Next-Gen Radar Perception

SDK

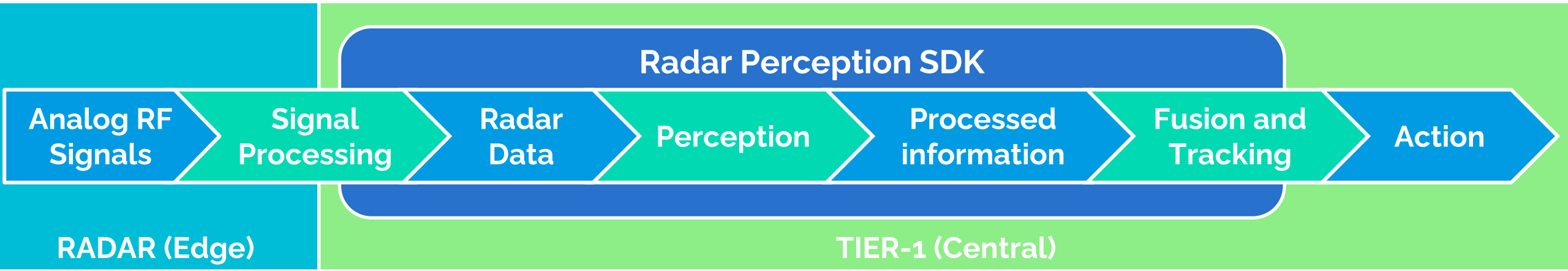
**Software defined**

**AI Driven**

**Hardware agnostic**



**Fusion ready**




PERCIVAI

# Radar Perception SDK

PERCIVAI

# Radar Perception SDK

PERCIVAI

# Radar Perception SDK

## PREPROCESSING

- Low-level Data Processing
- Point Cloud Segmentation

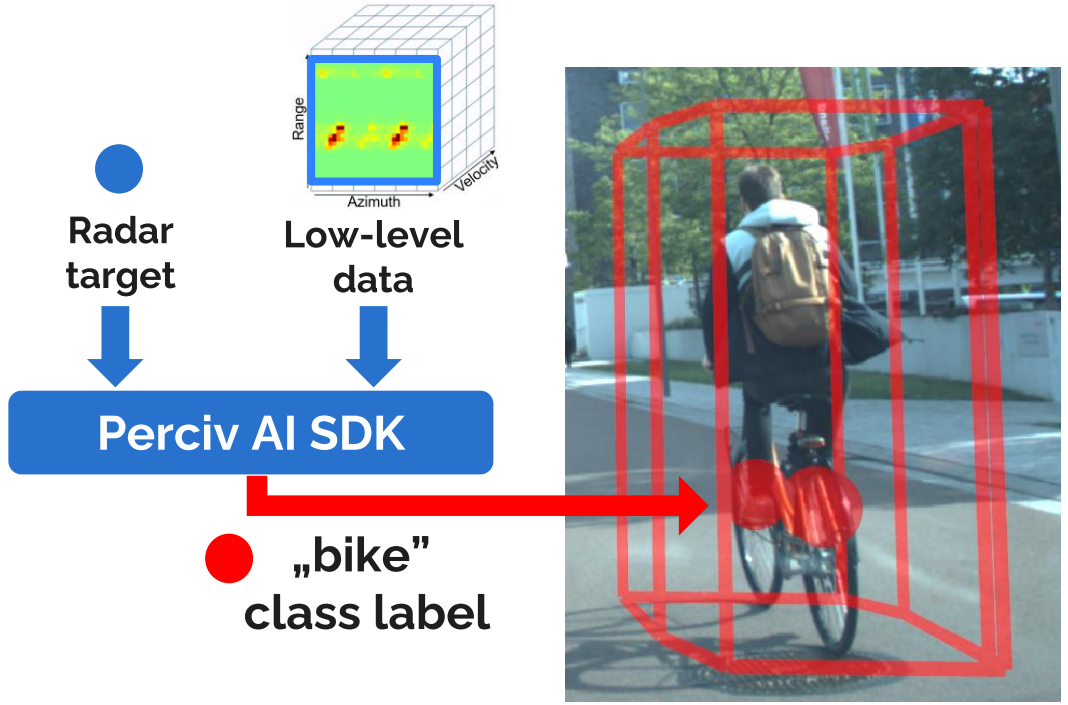
## FUSION

- Calibration
- Early/Late Fusion

## USE-CASES

- SLAM/Odometry
- NCAP Scenes
- Road User Detection
- Free Road Estimation

PERCIVAI




Cyclist Pedestrian

# Radar Perception SDK

## PREPROCESSING

- Low-level Data Processing
- Point Cloud Segmentation

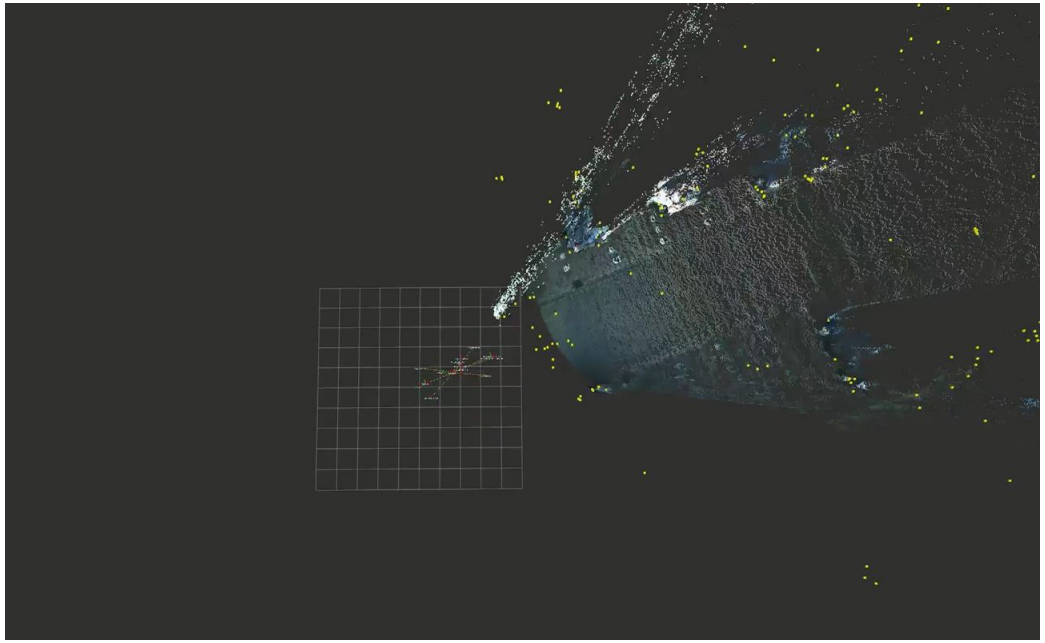
## FUSION

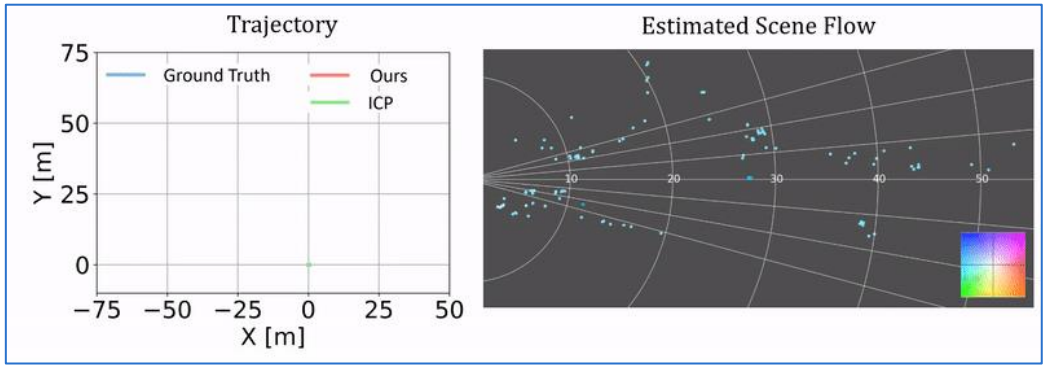
- Calibration
- Early/Late Fusion

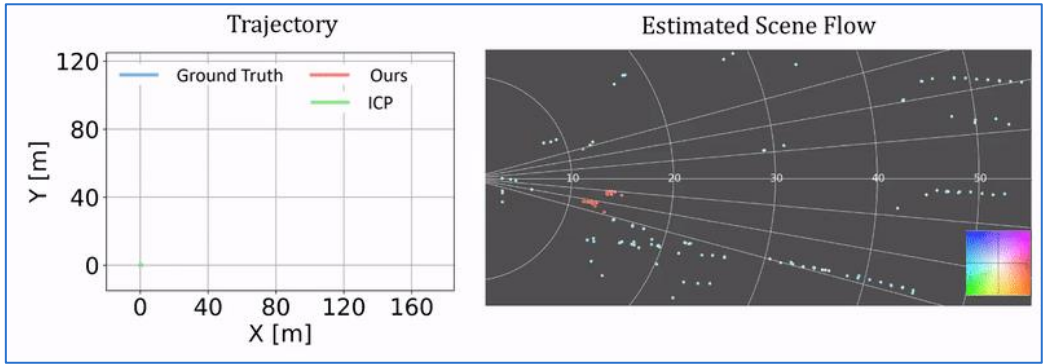
## USE-CASES

- SLAM/Odometry
- NCAP Scenes
- Road User Detection
- Free Road Estimation

PERCIVAI





# Radar Perception SDK

## PREPROCESSING

- Low-level Data Processing
- Point Cloud Segmentation

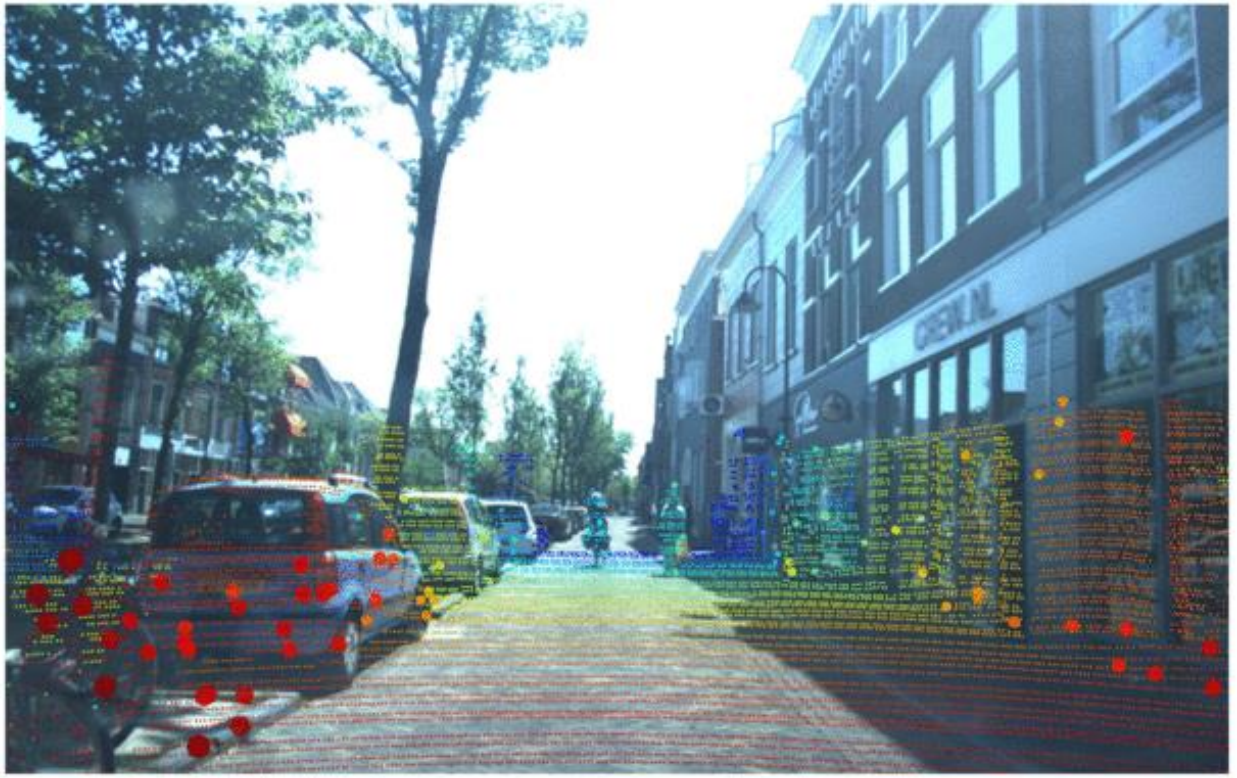
## FUSION

- Calibration
- Early/Late Fusion

## USE-CASES

- SLAM/Odometry
- NCAP Scenes
- Road User Detection
- Free Road Estimation

PERCIVAI



# Radar Perception SDK

## PREPROCESSING

- Low-level Data Processing
- Point Cloud Segmentation

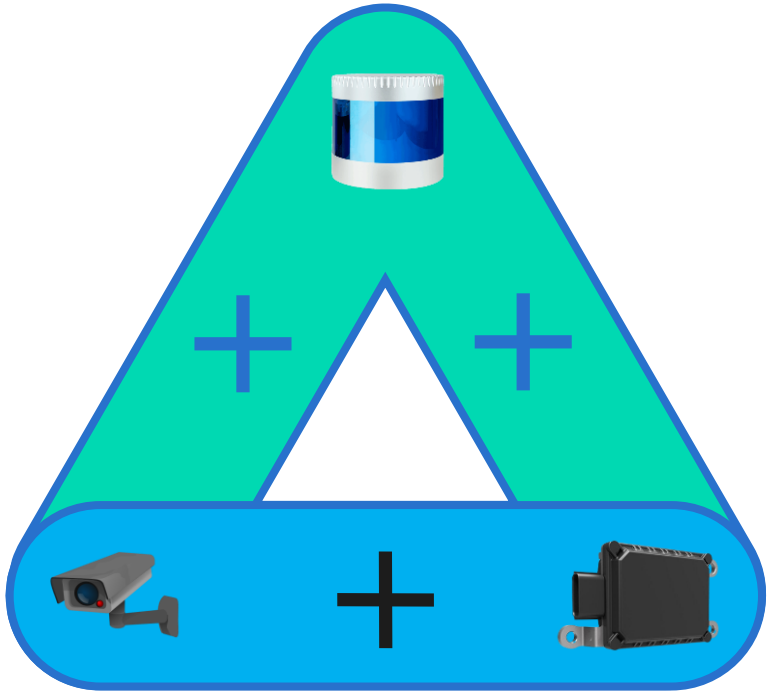
## FUSION

- Calibration
- Early/Late Fusion

## USE-CASES

- SLAM/Odometry
- NCAP Scenes
- Road User Detection
- Free Road Estimation

PERCIVAI



# Radar Perception SDK

## PREPROCESSING

- Low-level Data Processing
- Point Cloud Segmentation

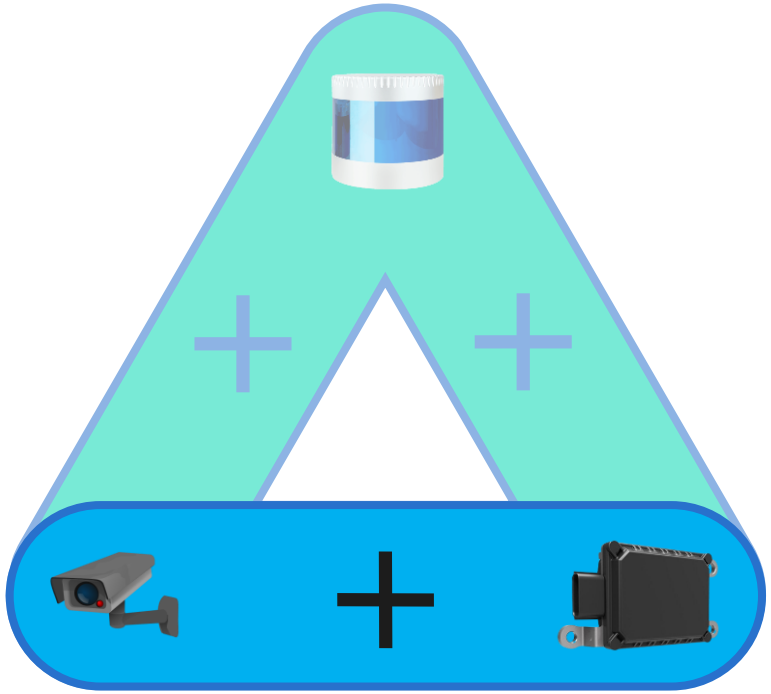
## FUSION

- Calibration
- Early/Late Fusion

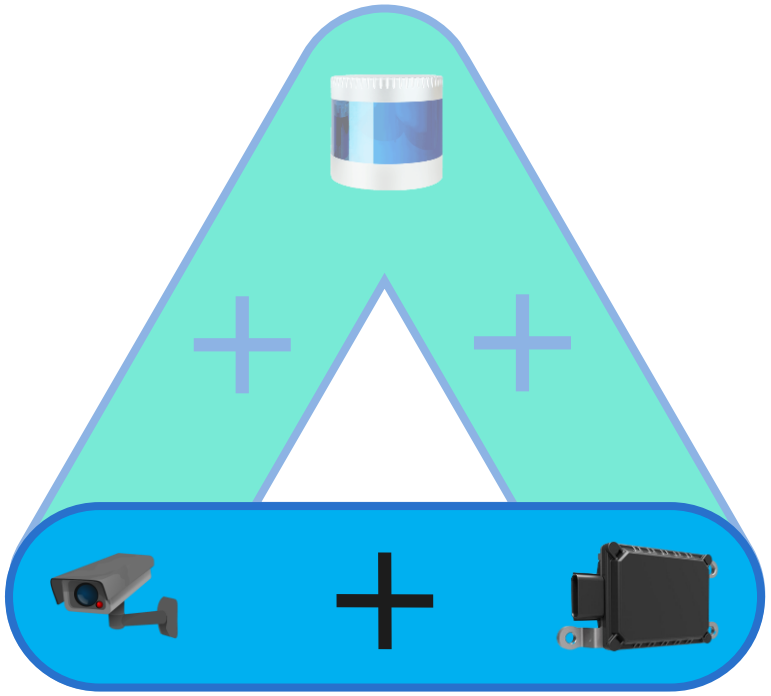
## USE-CASES

- SLAM/Odometry
- NCAP Scenes
- Road User Detection
- Free Road Estimation

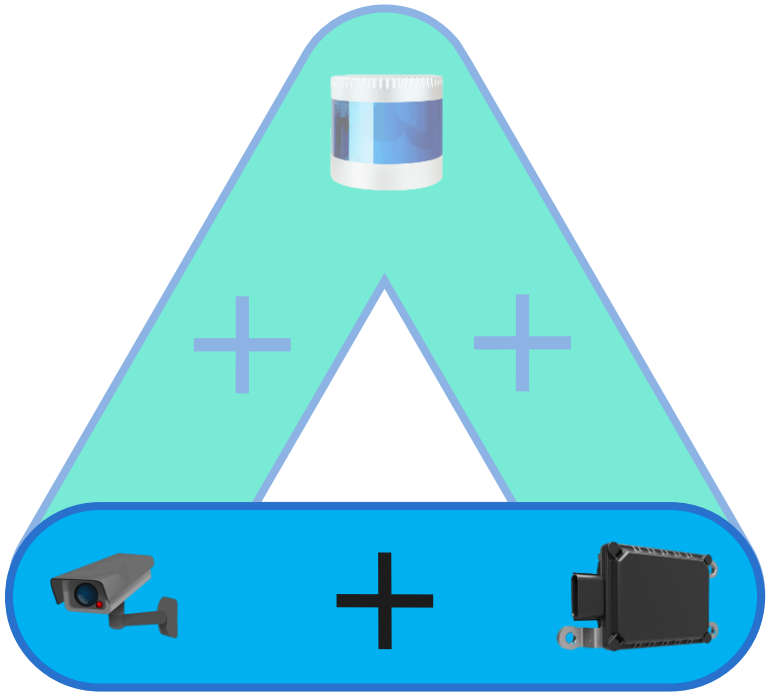
PERCIVAI



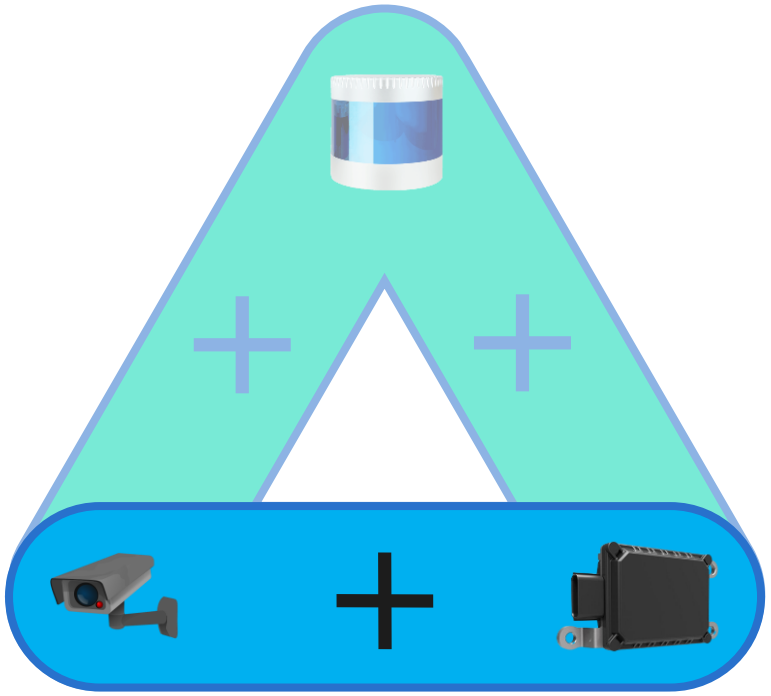
# Radar – camera sensor fusion



# Radar – camera sensor fusion

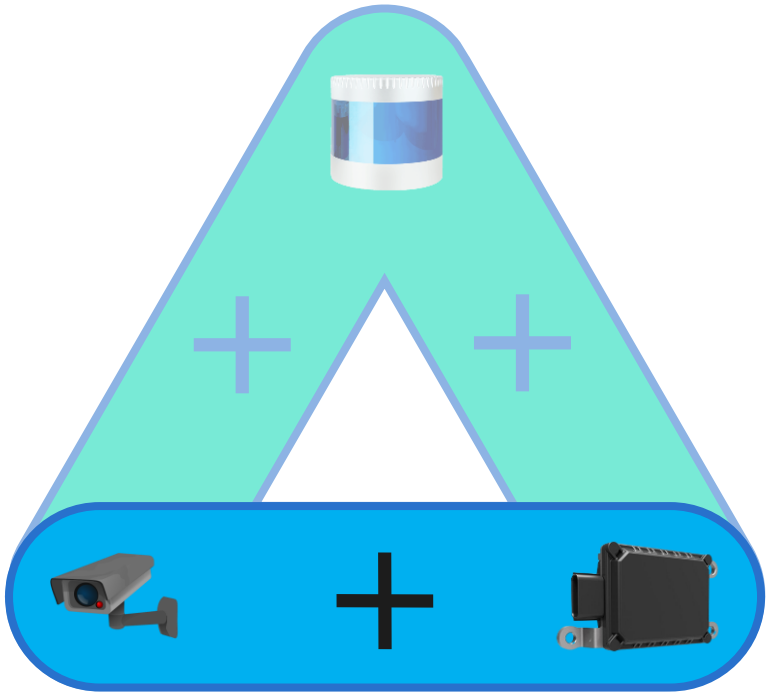


# Radar – camera sensor fusion



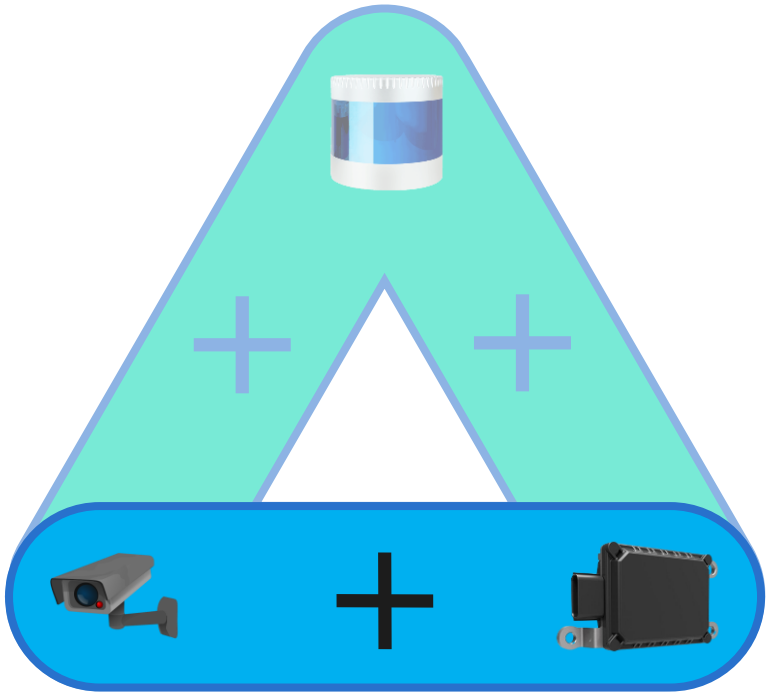
| | | |
|---|---|---|
| Dense 2D data | ✓ | ✗ |
| | | |
| | | |

# Radar – camera sensor fusion



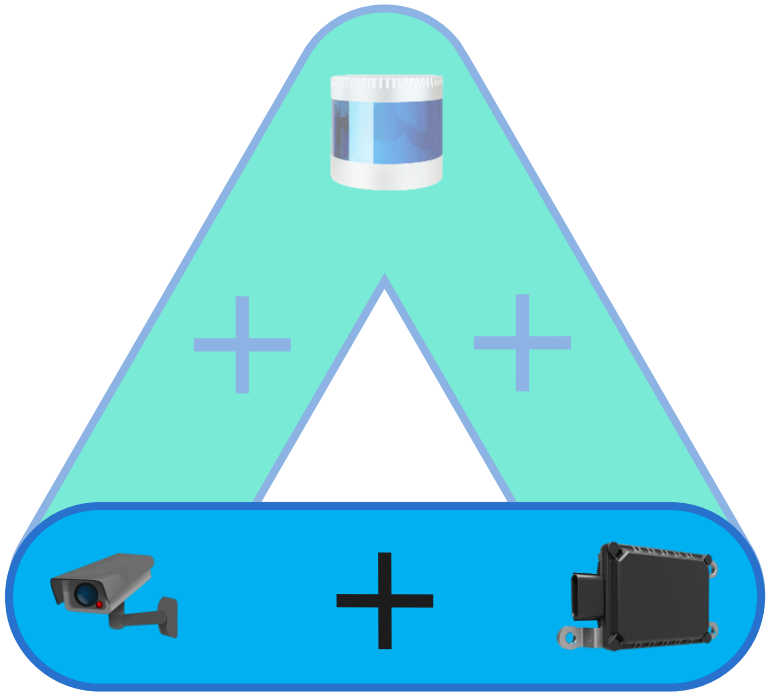
| |  |  |
|---|---|---|
| Dense 2D data | ✓ | ✗ |
| Accurate range data | ✗ | ✓ |

# Radar – camera sensor fusion



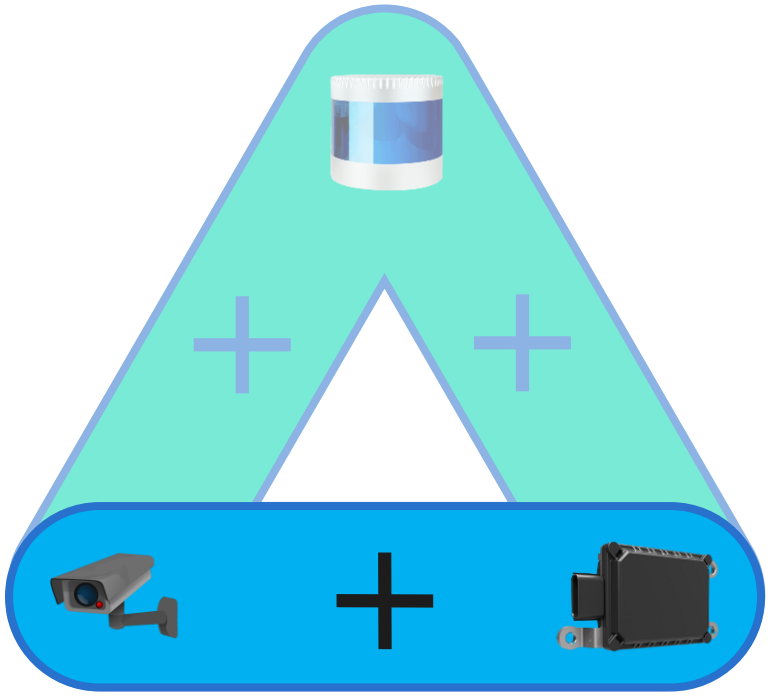
| |  |  |  |
|---|---|---|---|
| Dense 2D data | ✓ | ✗ | ✓ |
| Accurate range data | ✗ | ✓ | ✓ |

# Radar – camera sensor fusion



| |  |  |  |
|---|---|---|---|
| Dense 2D data | ✓ | ✗ | ✓ |
| Accurate range data | ✗ | ✓ | ✓ |
| Market ready price point | ✓ | ✓ | ✗ |

# Radar – camera sensor fusion with LiDAR supervision



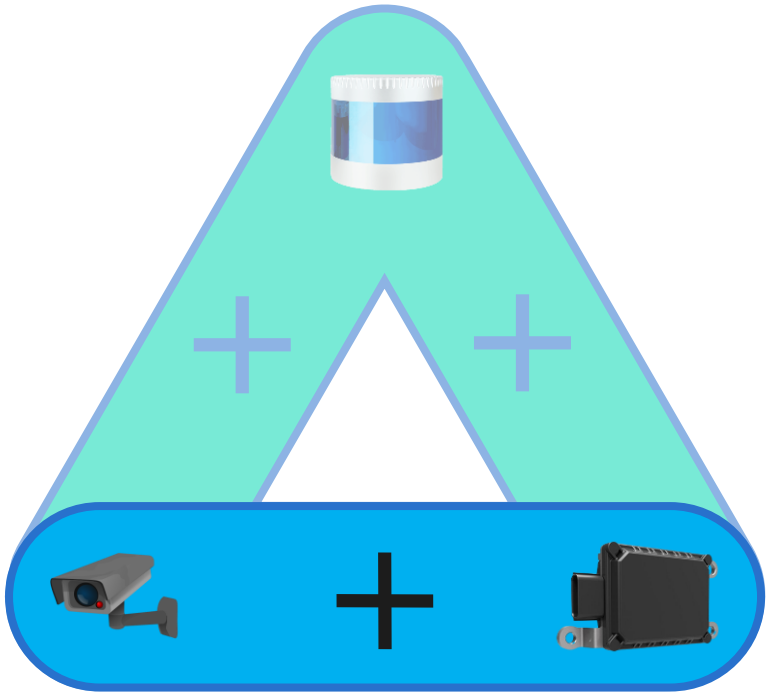
| | | | |
|---|---|---|---|
| Dense 2D data | ✓ | ✗ | ✓ |
| Accurate range data | ✗ | ✓ | ✓ |
| Market ready price point | ✓ | ✓ | ✗ |

Funded by the European Union

EVENTS project has received funding under grant agreement No 101069614. It is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the granting authority can be held responsible for them.

EVENTS

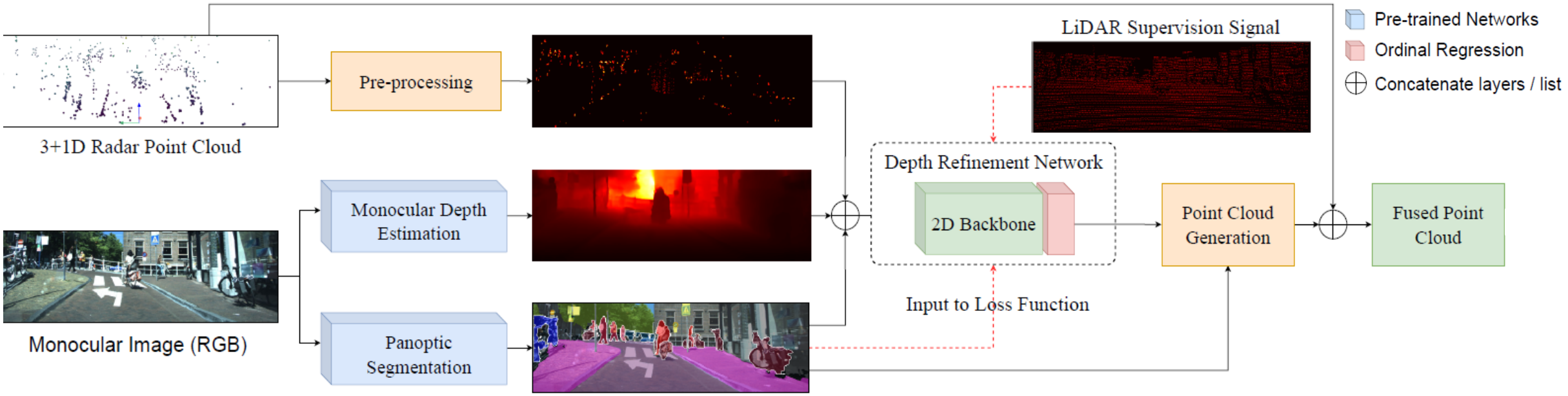
# Radar – camera sensor fusion with LiDAR supervision



| | | | |
|---|---|---|---|
| Dense 2D data | ✓ | ✗ | ✓ |
| Accurate range data | ✗ | ✓ | ✓ |
| Market ready price point | ✓ | ✓ | ✗ |

We cannot put a LiDAR in every car –
but maybe it is enough to put it in one!

# Overview

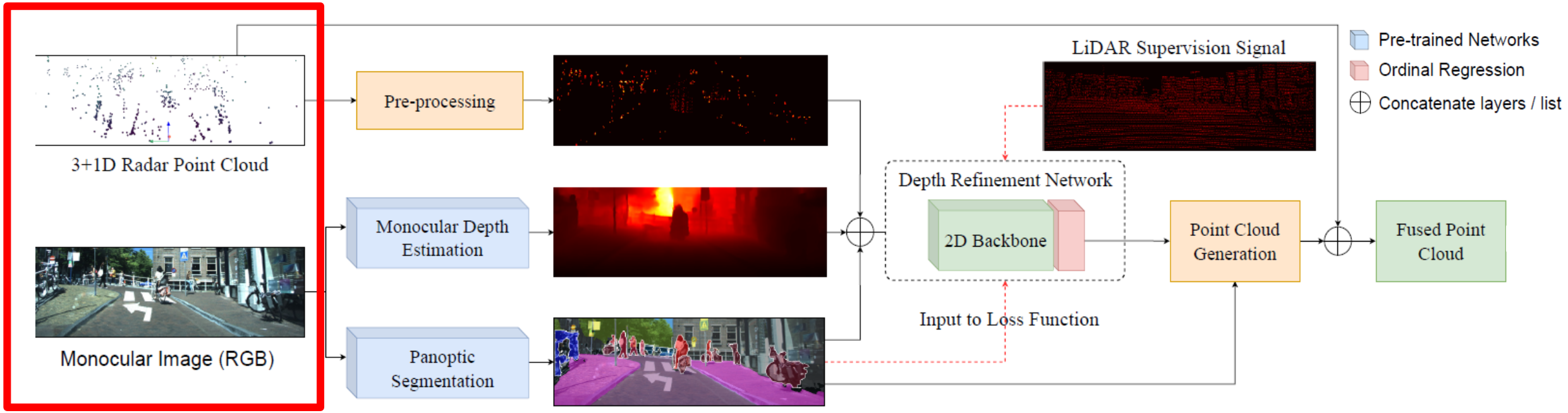



Funded by the European Union

EVENTS project has received funding under grant agreement No 101069614. It is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the granting authority can be held responsible for them.

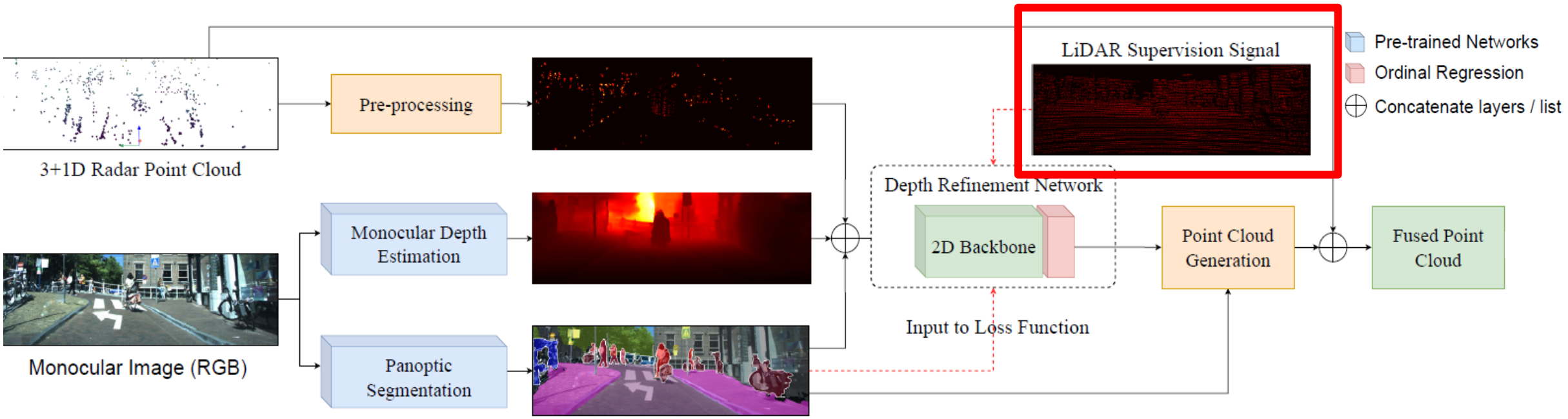
PERCIVAI

# Input sensors: radar + camera



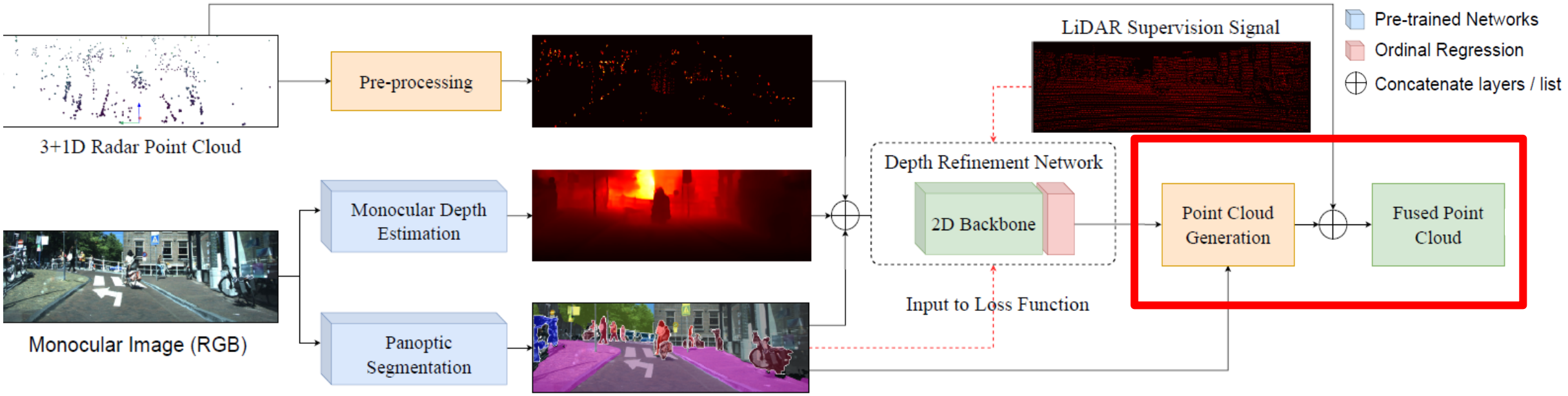

PERCIVAI

# Training sensor: LiDAR



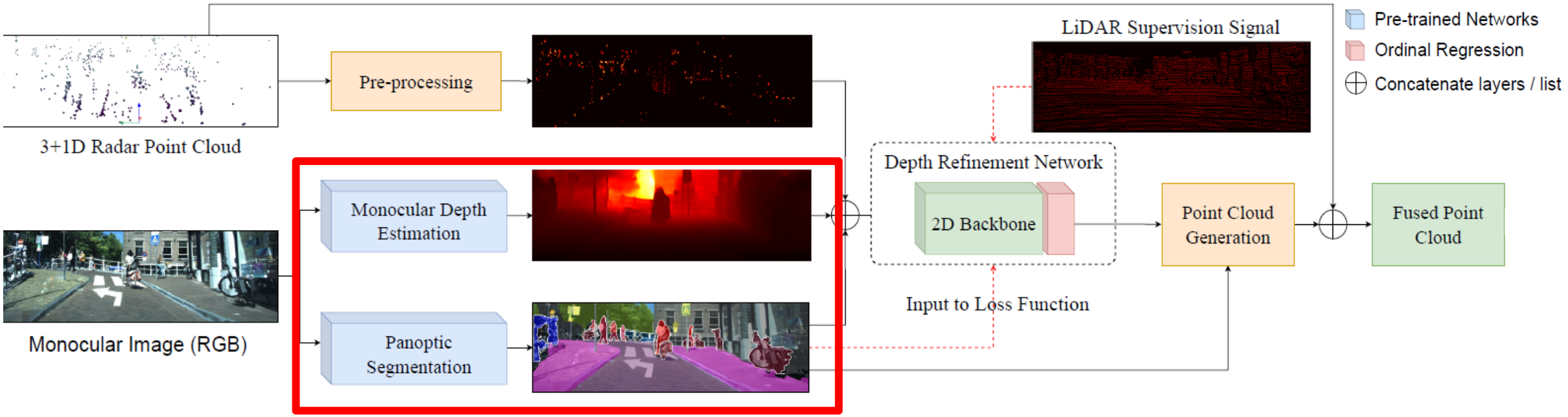

PERCIVAI

# Output: LiDAR-like point cloud



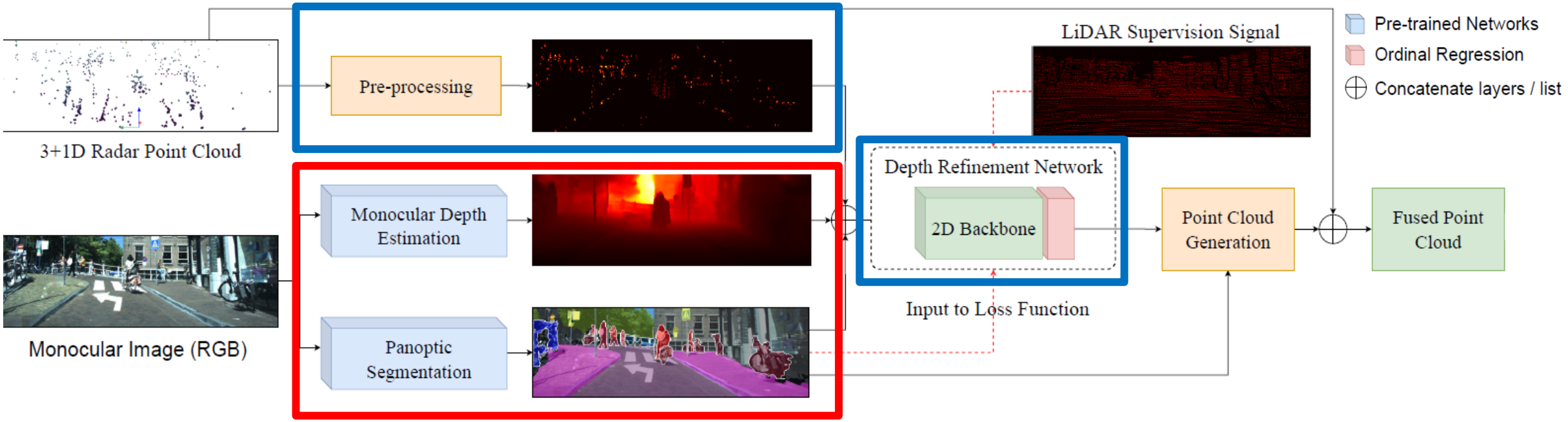

PERCIVAI

# Common perception modules



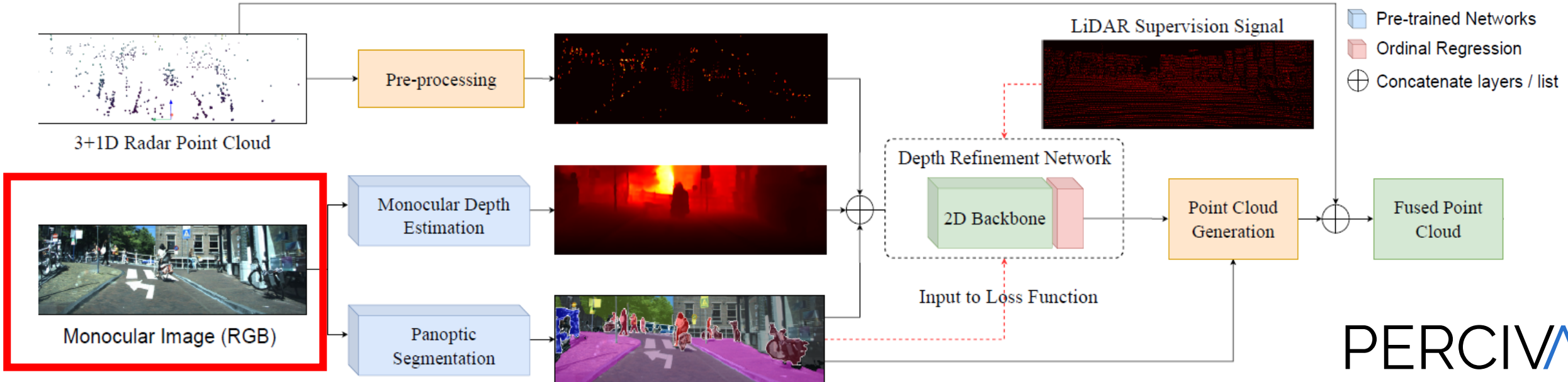

PERCIVAI

# Additional perception modules



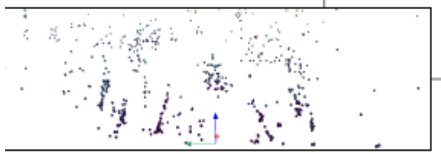

Additional steps are relatively lightweight!

PERCIVAI


3+1D Radar Point Cloud
Pre-processing
Monocular Image (RGB)
Monocular Depth Estimation
Panoptic Segmentation
LiDAR Supervision Signal
Depth Refinement Network
2D Backbone
Input to Loss Function
Point Cloud Generation
Fused Point Cloud
Pre-trained Networks
Ordinal Regression
Concatenate layers / list

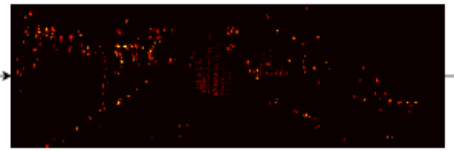
PERCIVAI

LiDAR

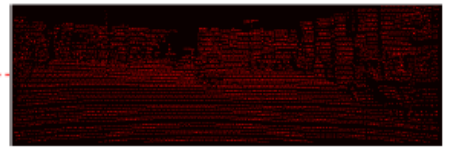


3+1D Radar Point Cloud

Pre-processing



LiDAR Supervision Signal



Pre-trained Networks

Ordinal Regression

Concatenate layers / list

Monocular Image (RGB)

Monocular Depth Estimation

Panoptic Segmentation

Depth Refinement Network

2D Backbone

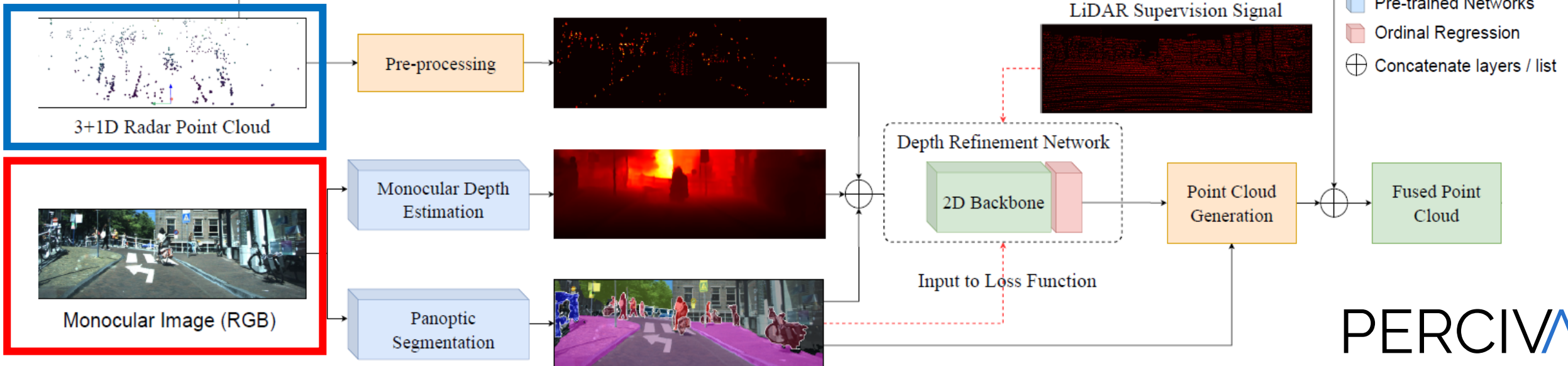
Input to Loss Function

Point Cloud Generation

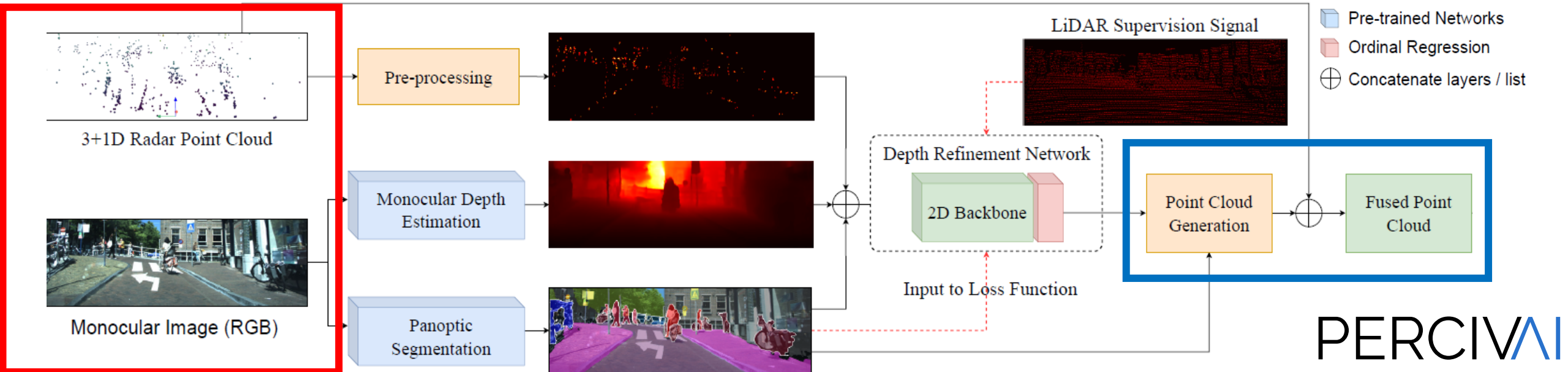
Fused Point Cloud

PERCIVAI

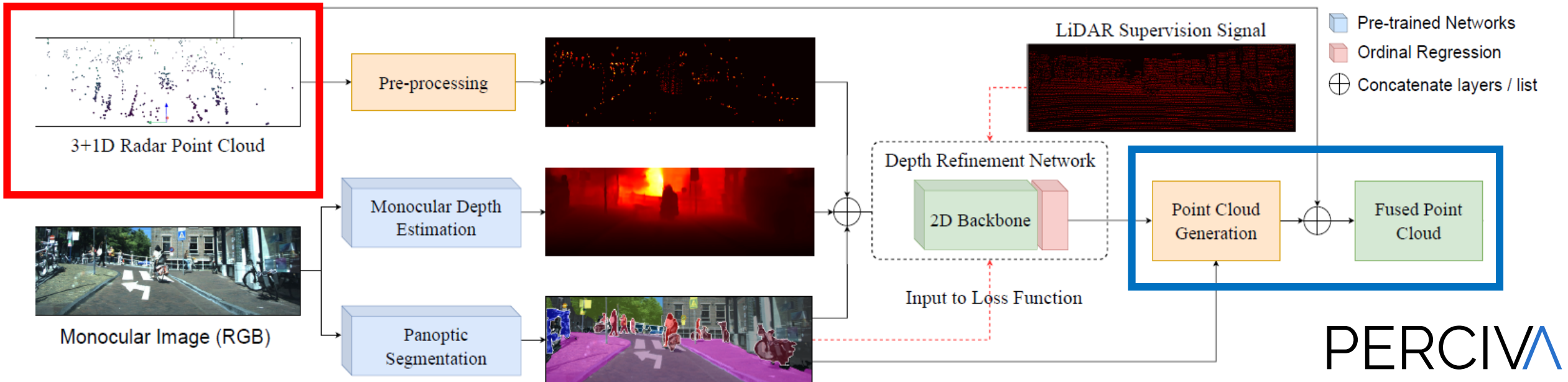
Radar



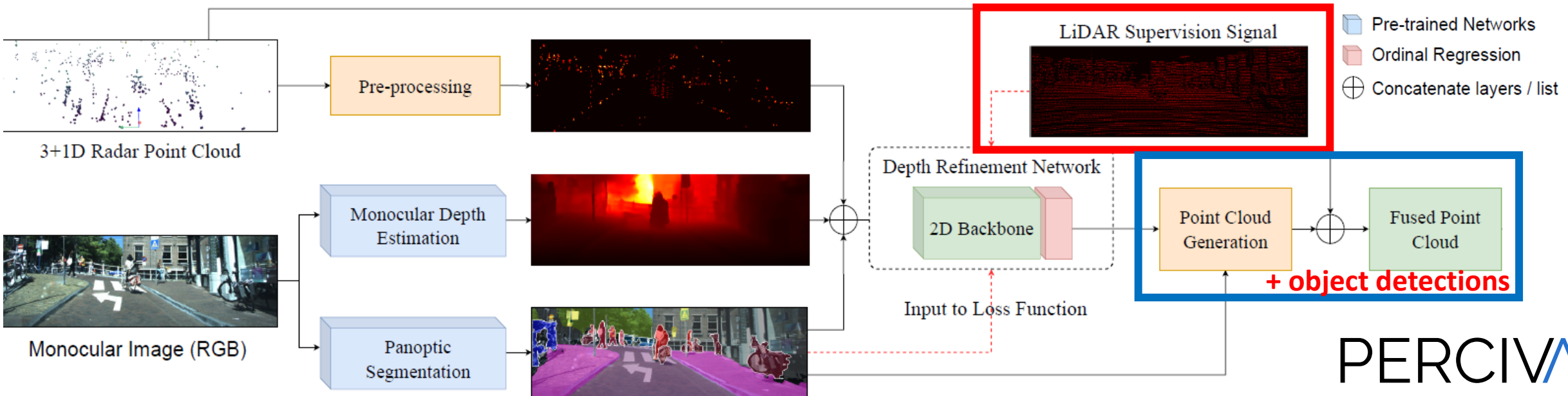

PERCIVAI


3+1D Radar Point Cloud
Monocular Image (RGB)
Pre-processing
Monocular Depth Estimation
Panoptic Segmentation
LiDAR Supervision Signal
Depth Refinement Network
2D Backbone
Input to Loss Function
Point Cloud Generation
Fused Point Cloud
Pre-trained Networks
Ordinal Regression
Concatenate layers / list

PERCIVAI


3+1D Radar Point Cloud
Pre-processing
Monocular Image (RGB)
Monocular Depth Estimation
Panoptic Segmentation
LiDAR Supervision Signal
Depth Refinement Network
2D Backbone
Input to Loss Function
Point Cloud Generation
Fused Point Cloud
Pre-trained Networks
Ordinal Regression
Concatenate layers / list

PERCIVAI


3+1D Radar Point Cloud
Pre-processing
Monocular Image (RGB)
Monocular Depth Estimation
Panoptic Segmentation
LiDAR Supervision Signal
Depth Refinement Network
2D Backbone
Input to Loss Function
Point Cloud Generation
Fused Point Cloud
+ object detections
Pre-trained Networks
Ordinal Regression
Concatenate layers / list

PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

PERCIVAI

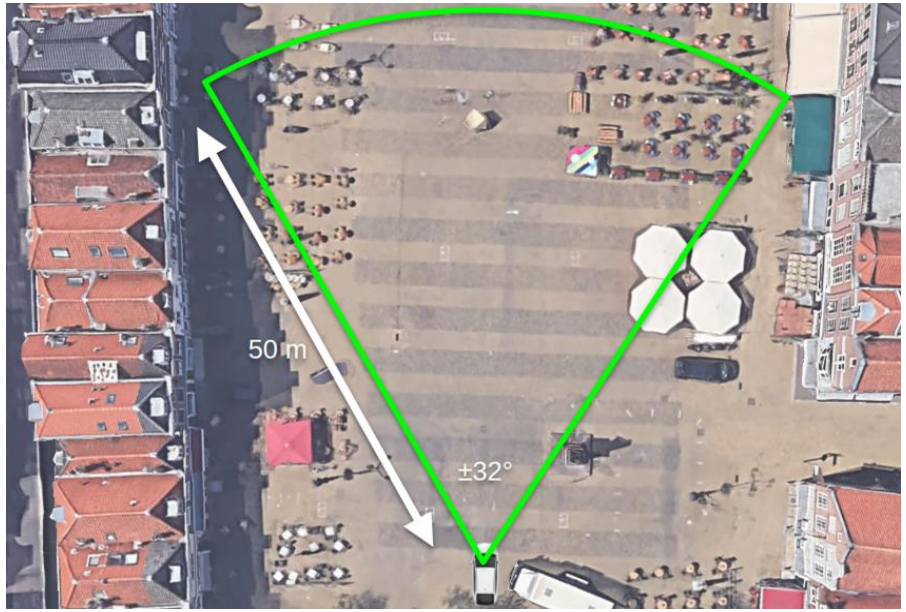
# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | pain | | | | | | | | | | |
| PP - radar | rada | | | | | | | | | | |
| PP - RAID fusion | pain | | | | | | | | | | |
| PP - LiDAR | LiD | | | | | | | | | | |
| PP - LiDAR (painted) | pain | | | | | | | | | | |





PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

PERCIVAI

# Quantitative results

| Method | Input to Detection Network | Entire annotated area | | | | | In Driving Corridor | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Car | Pedestrian | Cyclist | mAP | mAOS | Car | Pedestrian | Cyclist | mAP | mAOS |
| PP - mono (painted) | painted monocular pcl | 18.2 | 10.1 | 7.9 | 12.1 | 21.9 | 45.6 | 12.6 | 19.7 | 26.0 | 37.8 |
| PP - radar | radar pcl | 41.1 | 41.0 | 54.5 | 45.6 | 38.3 | 77.7 | 59.3 | 76.4 | 71.1 | 64.1 |
| PP - RAID fusion | painted RAID pcl + radar pcl | 51.8 | 50.6 | 57.3 | 53.2 | 48.4 | 89.7 | 68.9 | 83.7 | 80.8 | **75.1** |
| PP - LiDAR | LiDAR pcl | 75.6 | 55.1 | 55.4 | 62.1 | 49.4 | 90.8 | 71.4 | 82.5 | 81.6 | 70.3 |
| PP - LiDAR (painted) | painted LiDAR pcl | **77.2** | **62.2** | **57.6** | **65.7** | **51.1** | **90.9** | **79.2** | **85.6** | **85.3** | 70.6 |

| | | | |
|---|---|---|---|
| PP - RAID fusion | 89.7 | 68.9 | 83.7 |
| PP - LiDAR | 90.8 | 71.4 | 82.5 |

PERCIVAI


Fusion


PERCIVAI



- ✓ Radar-camera fusion

PERCIVAI



- ✓ Radar-camera fusion
- ✓ supervised by LiDAR

PERCIVAI



- ✓ Radar-camera fusion
- ✓ supervised by LiDAR
- ✓ LiDAR-like output point cloud

PERCIVAI

Fusion


- ✓ Radar-camera fusion
- ✓ supervised by LiDAR
- ✓ LiDAR-like output point cloud
- ✓ Comparable results in object detection to LiDAR

PERCIVAI


Fusion


- ✓ Radar-camera fusion
- ✓ supervised by LiDAR
- ✓ LiDAR-like output point cloud
- ✓ Comparable results in object detection to LiDAR
  - ✓ Especially close-by

PERCIVAI


Fusion


- ✓ Radar-camera fusion
- ✓ supervised by LiDAR
- ✓ LiDAR-like output point cloud
- ✓ Comparable results in object detection to LiDAR
  - ✓ Especially close-by
  - ✓ Especially for cyclists

PERCIVAI



Dr. Andras Palffy

andras.palffy@perciv.ai

linkedin.com/in/
andraspalffy

PERCIVAI

See the invisible.
AI for radars.