CODAI 2023 Workshop

Temporal Patience

Efficient Adaptive Deep Learning for Embedded Radar Data Processing

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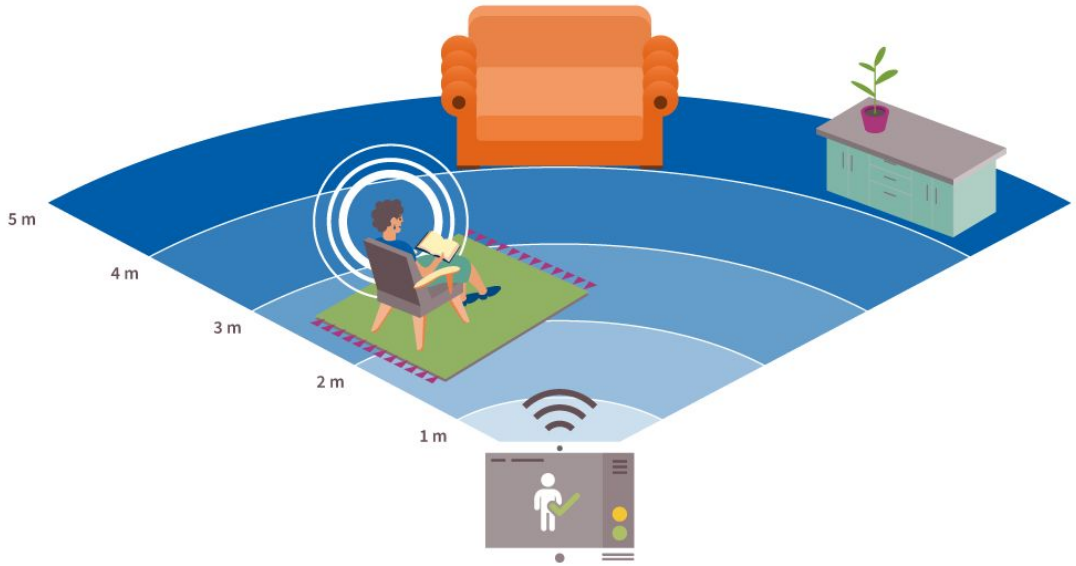
Radar-based People Counting

- Estimates the number of occupants in a given area

- all-in-one solution
  - “smart” sensor
  - Intelligent solution
  - Only outputs estimated number

- No…
  - Cloud infrastructure
  - Edge server
  - Network connection
  - Need for any additional compute



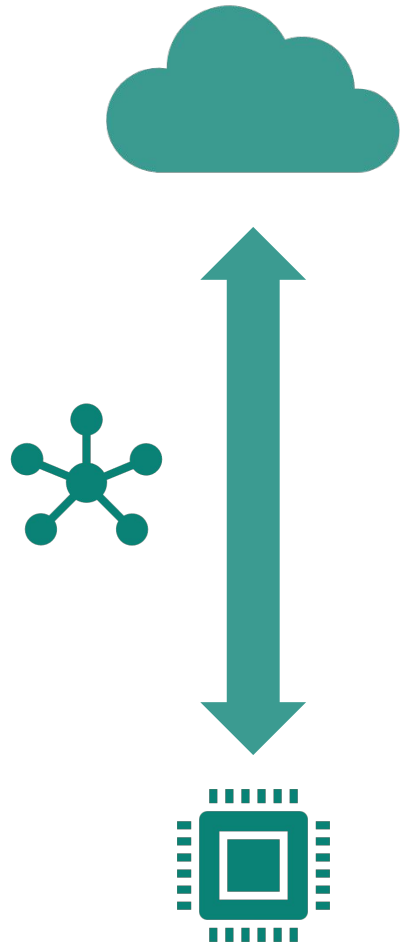
Benefits of local Processing

Privacy
- Data stays on the smart sensor
- Not send to any (third) party

Flexibility
- Can be deployed everywhere
- Easy to integrate into existing products

Independence
- No reliance on cloud
- No additional compute required
- No upkeep cost after sale
- No end-of-life due to API changes

Power Efficient
- Enables “virtual” always-on devices
- Powering down the main device
- Only smart sensor stays on



Problem: Performance

- Deployment has become easier
  - Modern toolchains automate most steps
  - Just need to find appropriate network architecture

- The solution works, but…
  - Rather slow
  - High power consumption

- Can we improve this further?
  - Further optimizations reduce accuracy too much

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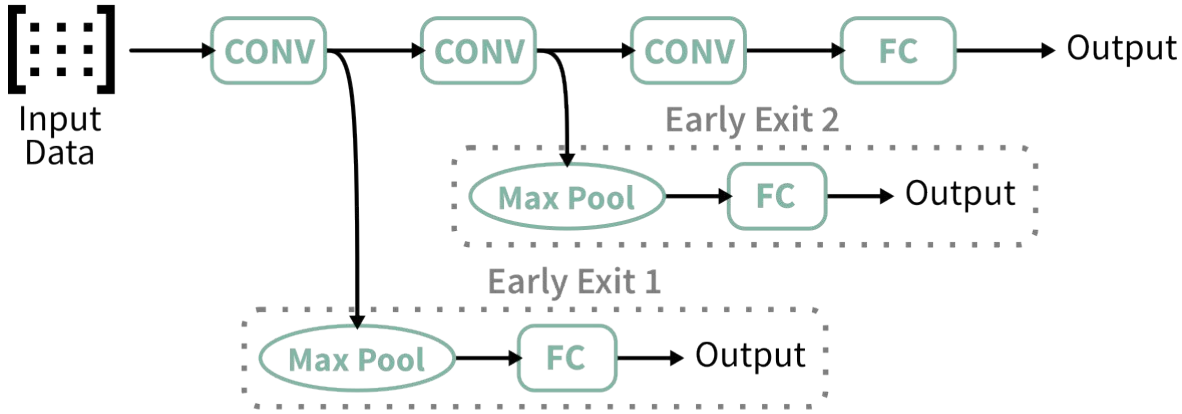
Adaptive Neural Networks

- Traditional Deep Learning: static
  - Neural Networks: no complex control flow
    - Easy to optimize/pre-plan execution
    - Limits its capabilities; every sample is treated the same
  - Optimizations: permanently impair prediction capabilities
    - Applied ahead-of-time
    - i.e. pruning, quantization, …
- Observation:
  - Not all samples are equal
  - “easy” and “hard” samples exist
- Adaptive Neural Networks:
  - Change structure and parameters at runtime
  - Depending on current circumstances (input, resources, …)

Early Exit Neural Networks

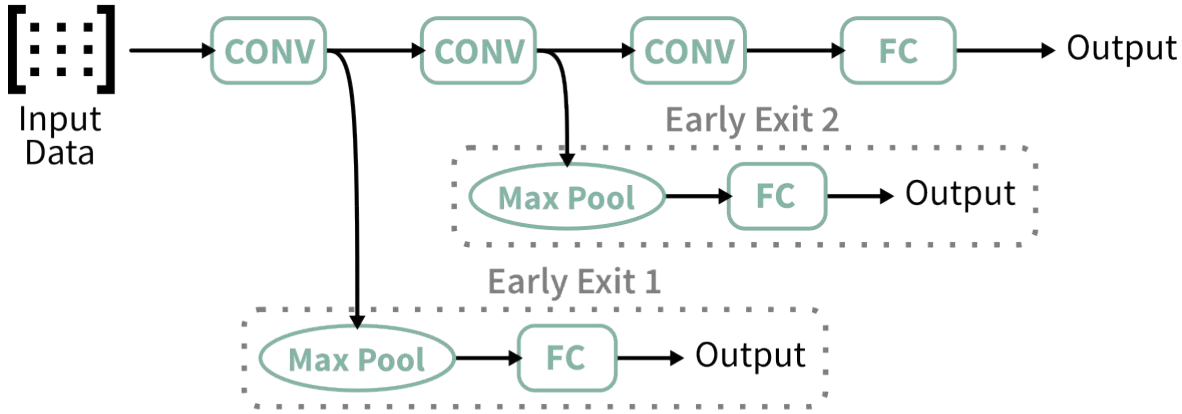
- Can terminate inference early
- Introduce Early Exits:
  - Additional classifiers
  - Between hidden layers
  - Trained for the same task as the final classifier
- Inference can be terminated if early result is sufficient
- Idea: Spend only as many resources as necessary
  - “Simple” data terminates early
  - “Hard” samples classified correctly by full network
- Can be seen as dynamic layer pruning



Early Exit Neural Networks

- Problem: how to decide when it is “sufficient”?
  - Small footprint, fast computation
  - Good decisions

- State-of-the-art
  - Rule-based:
    - Budget
    - Confidence
    - Patience
  - Agent-based:
    - Additional model
    - Trained to select classifier
    - Not suitable for embedded



Observations

- Radar sensor data is temporally correlated

- Subsequent samples are often similar
  - Time frame depends on the application
  - Conference room: hours/days without occupants

- Unnecessary to perform the entire inference again
- Just need to detect if it is similar
  - No reliable similarity metrics for radar data
  - Not expressive enough
  - Too expensive to run on every sample

- Idea: Monitor early results instead
  - Change in output should correlate to change in input
  - Utilizes extracted features that are relevant for task

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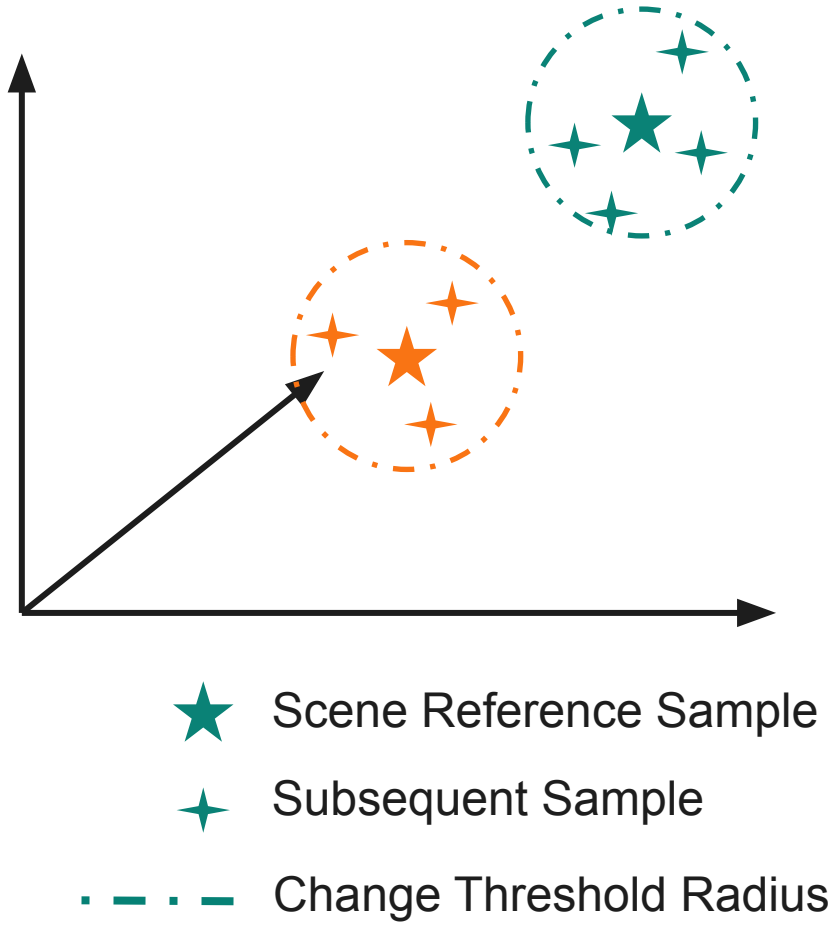
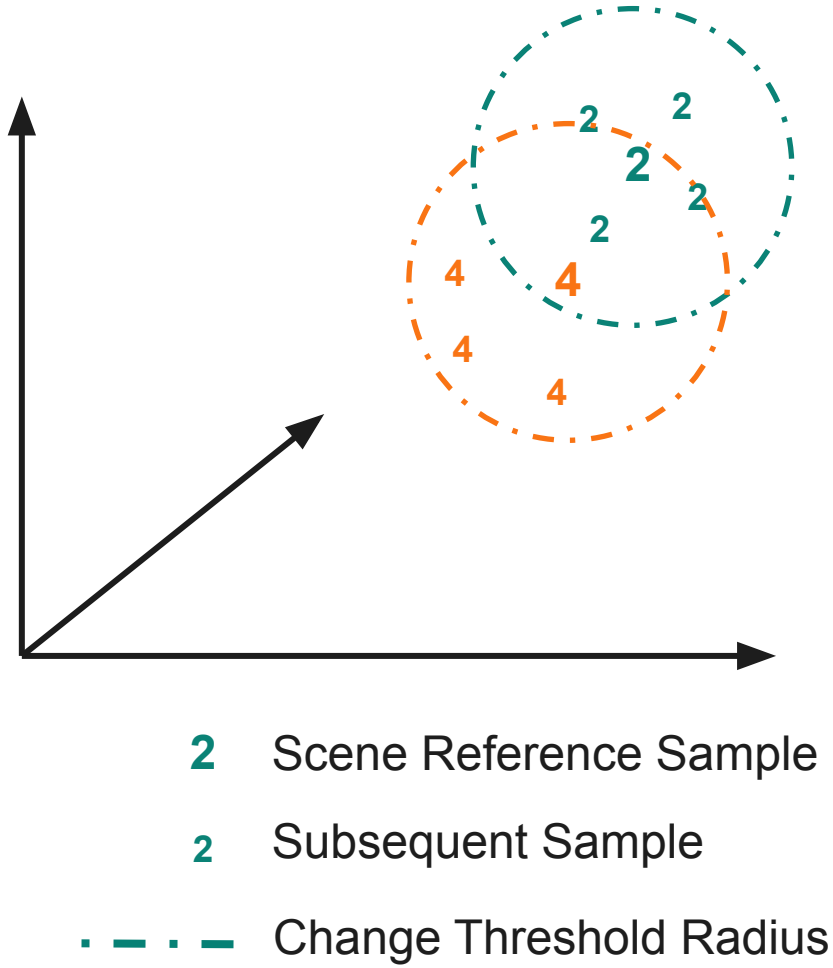
Difference Detection

- Observe change in first Early Exit
- Calculate distance, compare to threshold
  - If below threshold: terminate, reuse previous result
  - Otherwise: continue inference
- What to use as the reference:
  - Direct predecessor
  - would lead to accumulating small changes
  - “Scene Detection” instead
- “Scene”
  - Group of subsequent similar inputs
  - Always use the first sample as a reference
  - Only label the first sample by full inference
- New Scene:
  - Started by a sample that is different from previous



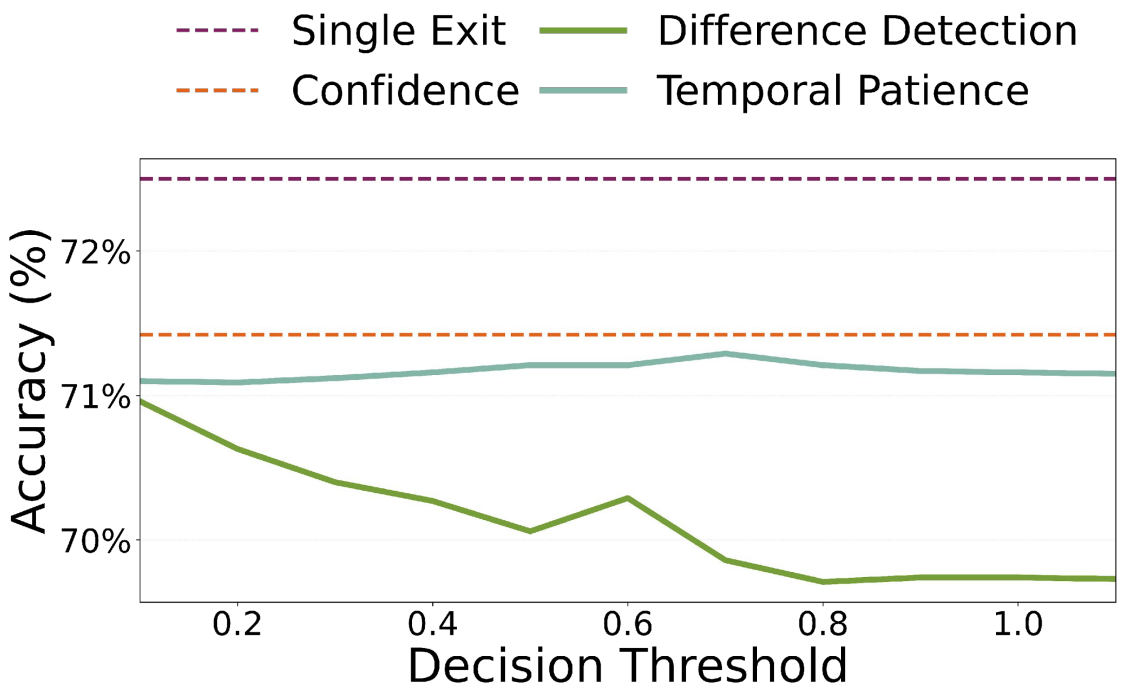
Temporal Patience

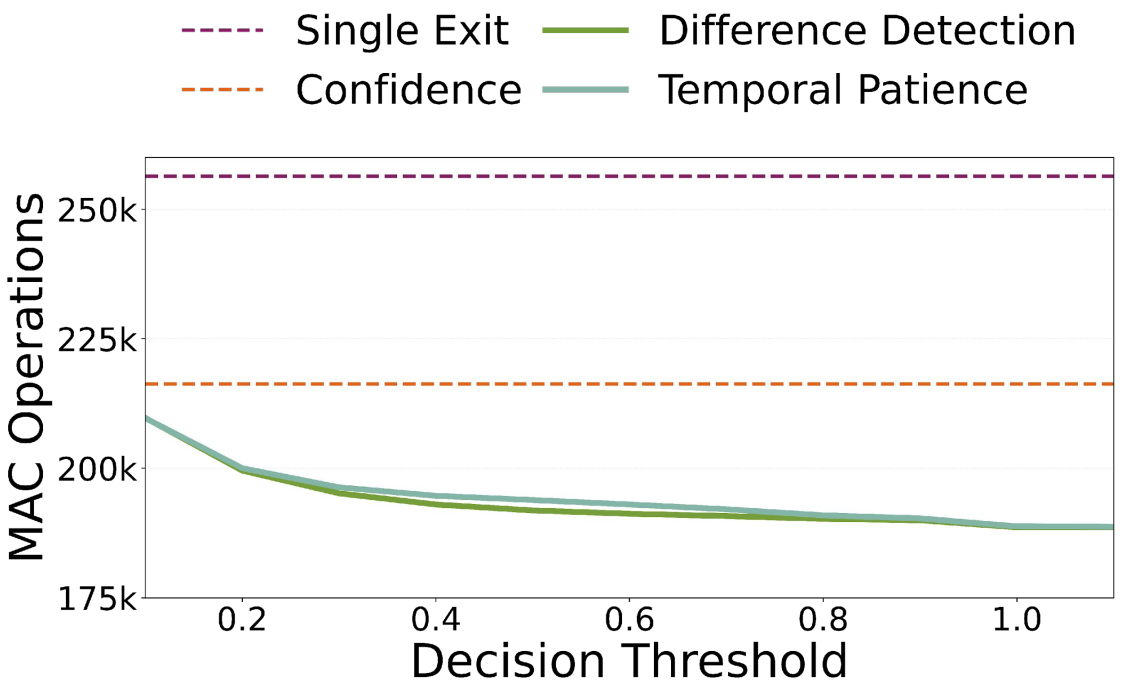
- Select used classifier dynamically
  - Higher computational cost
  - But increased accuracy
- Idea: use classifier that can detect relevant features
- New Scene Detection:
  - Not only reliant on distance
  - Also considers output label
  - Increases accuracy in ambiguous situations



Benchmark

- Evaluated the performance on radar recordings
- Duration: 30 seconds – 2 Minutes





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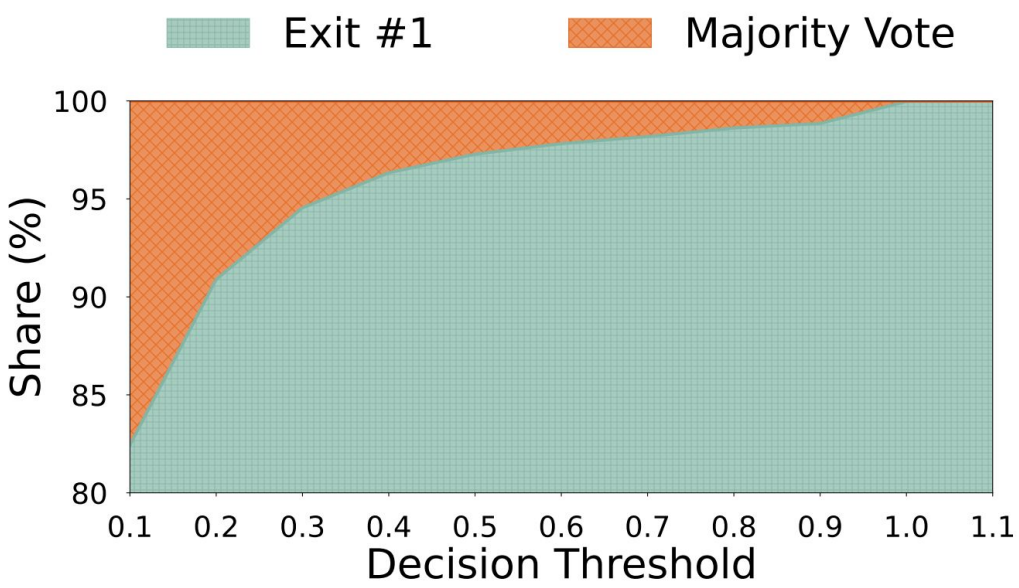
Difference Detection



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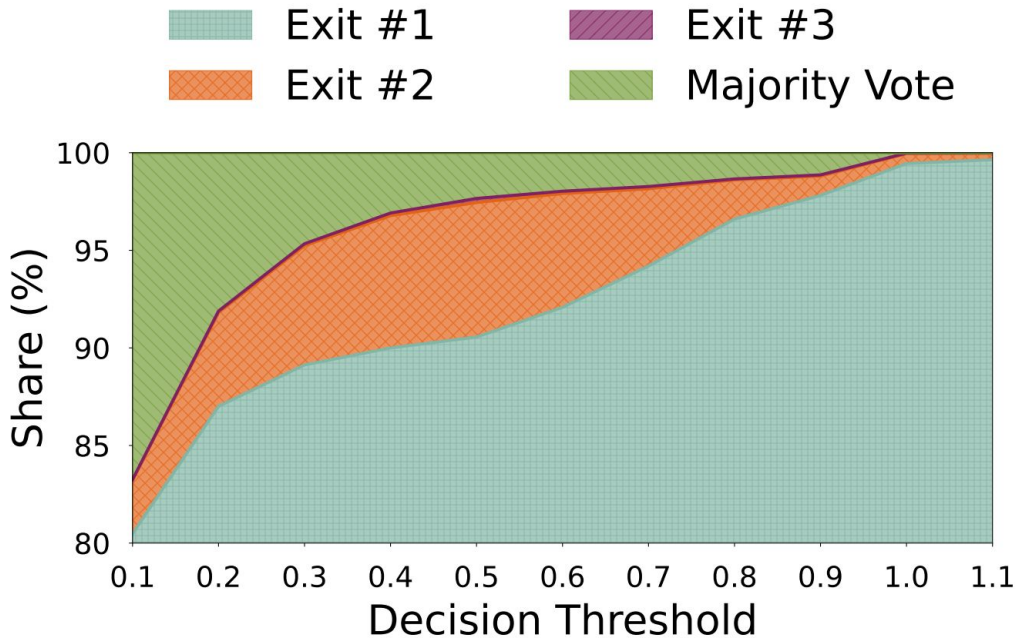

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Conclusion

- 26% less mean operations per inference

- Very early results
  - On a single application
  - Short recordings, even shorter Scenes
  - Applications with more static content could increase savings

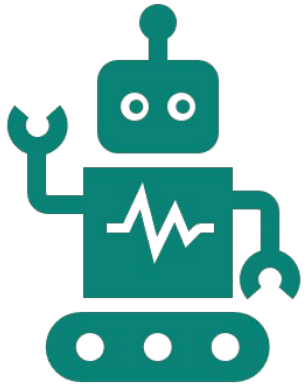
- Temporal Component:
  - RNN: leverage for prediction quality
  - Temporal Patience: leverage for better efficiency

  - Future research on utilizing it for increased efficiency

Future Work

- Different Data Modalities
  - Not only radar data is temporally correlated
  - IoT also utilizes various sensors
    - Microphones
    - Cameras
    - Specialized sensors

- Democratize Adaptive Deep Learning
  - Niche topic, not well known
  - Requires expertise
  - Enable automatic deployment
    - Search for a suitable Adaptive solution
    - Network adaptation method
    - At-runtime decision mechanism
    - Retraining of rewritten adaptive model



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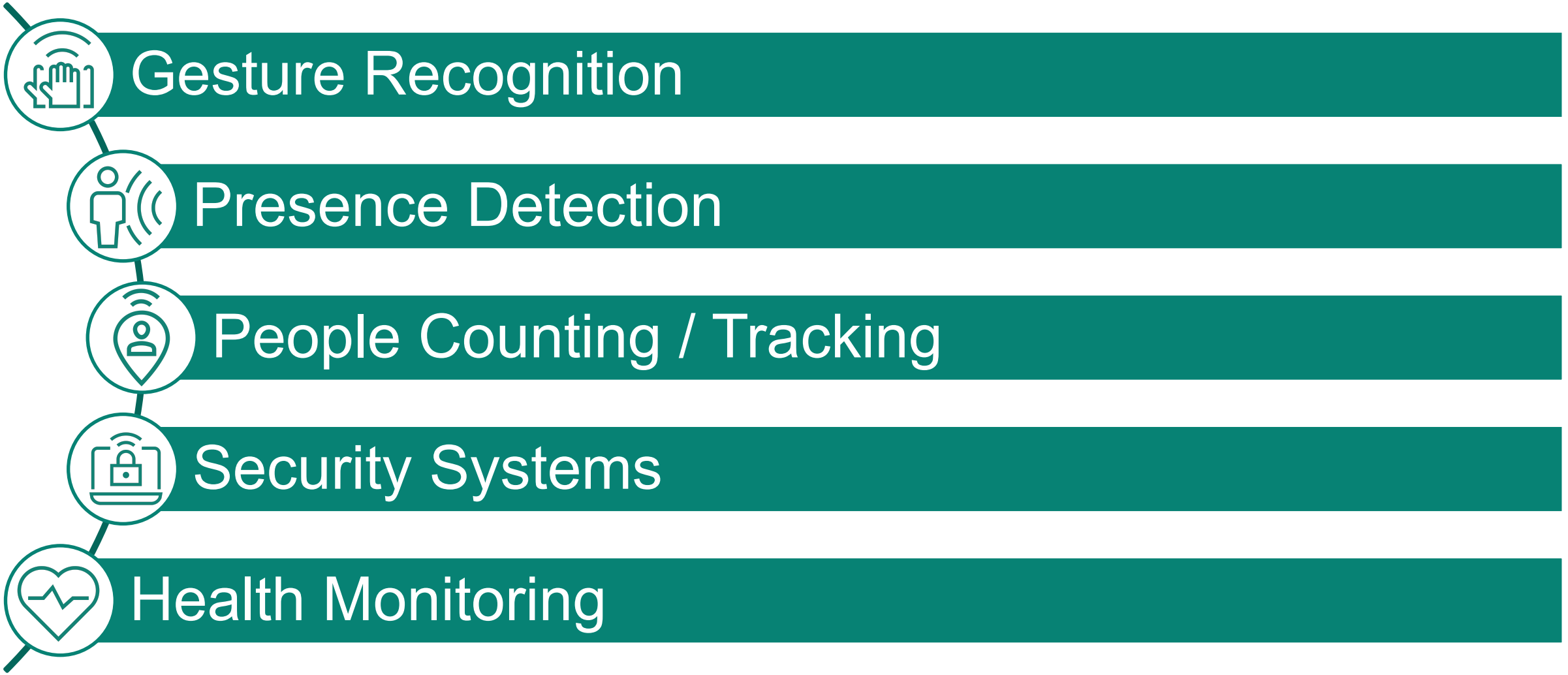
Applications for Radar Sensors in IoT



Applications for People Counting

Smart Home / Building

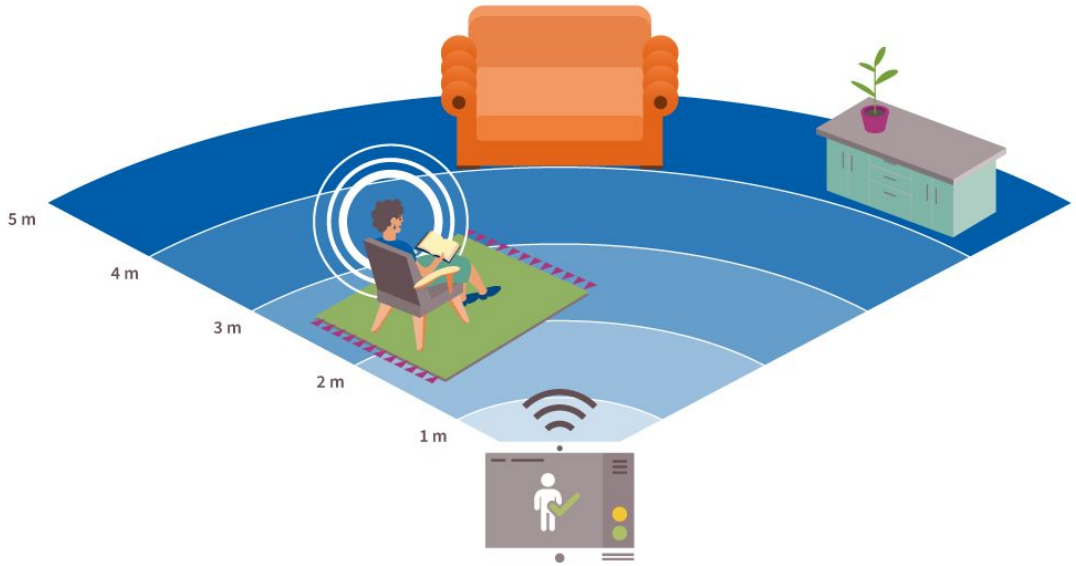
– Control building based on utilization

“Virtual” Always-On Devices

– Automatic wake-up
– Only active when users are present

Security Systems

– Alarm system
– Personal device privacy detection



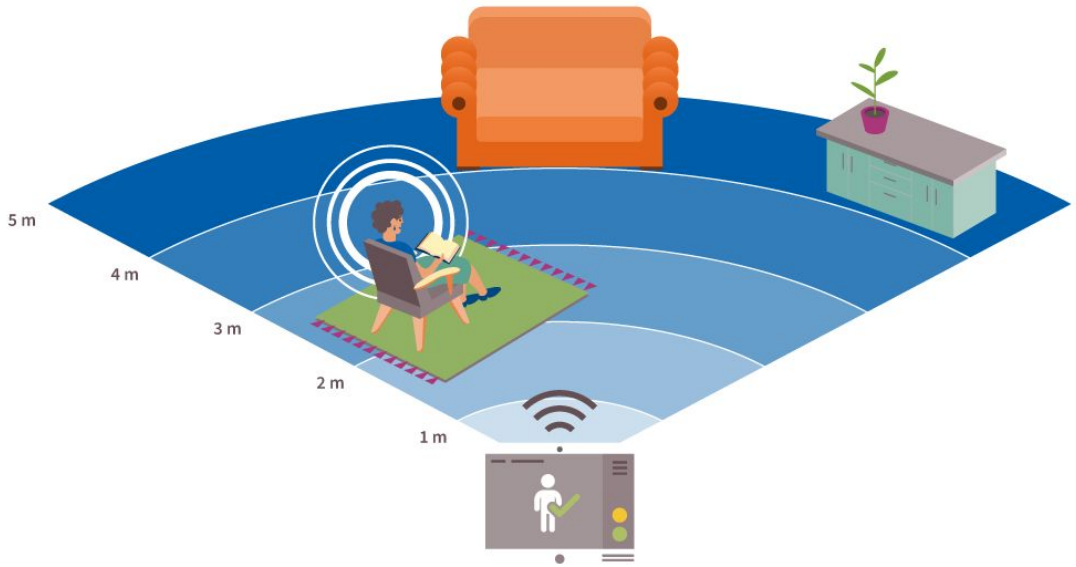
Application: Radar-based People Counting

- Task: Estimate the number of people
  - In a given area
  - Using radar sensor data

- Solution:
  - 60 GHz Radar Sensor
  - Cortex-M Microcontroller
  - Neural Network

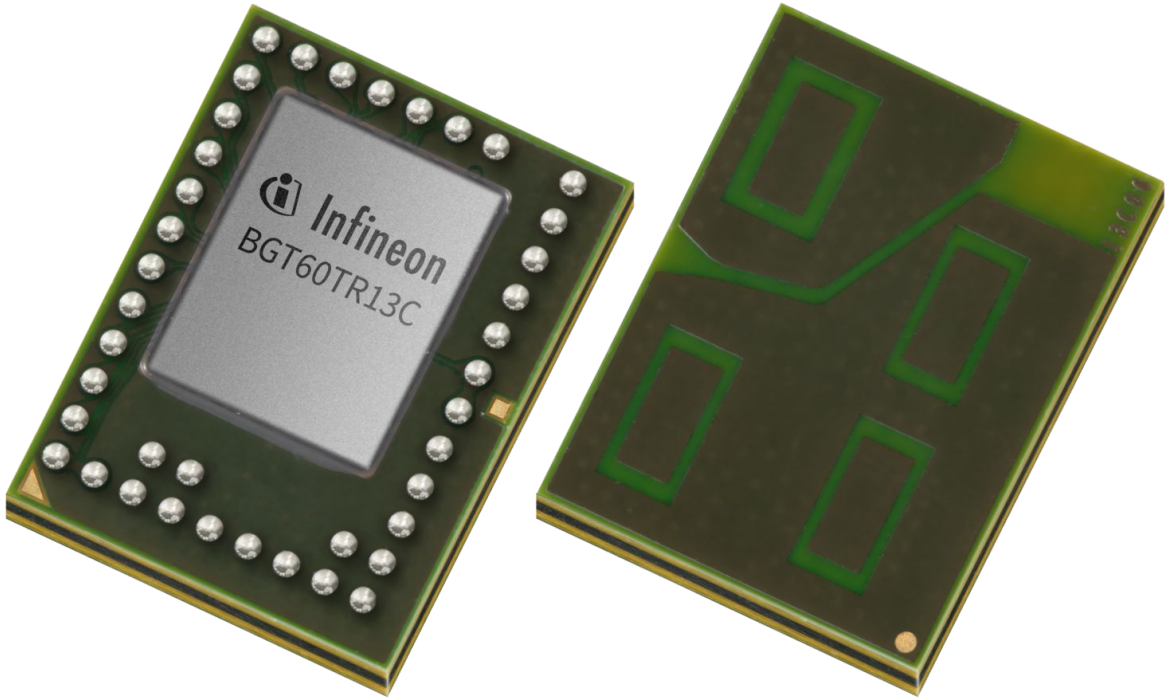
- Use case:
  - Home Automation
  - Always-on Devices
  - Security Features

- Problem:
  - Fitting the Workload onto the MCU
  - Preprocessing + Inference + Postprocessing
  - Minimize latency and power consumption

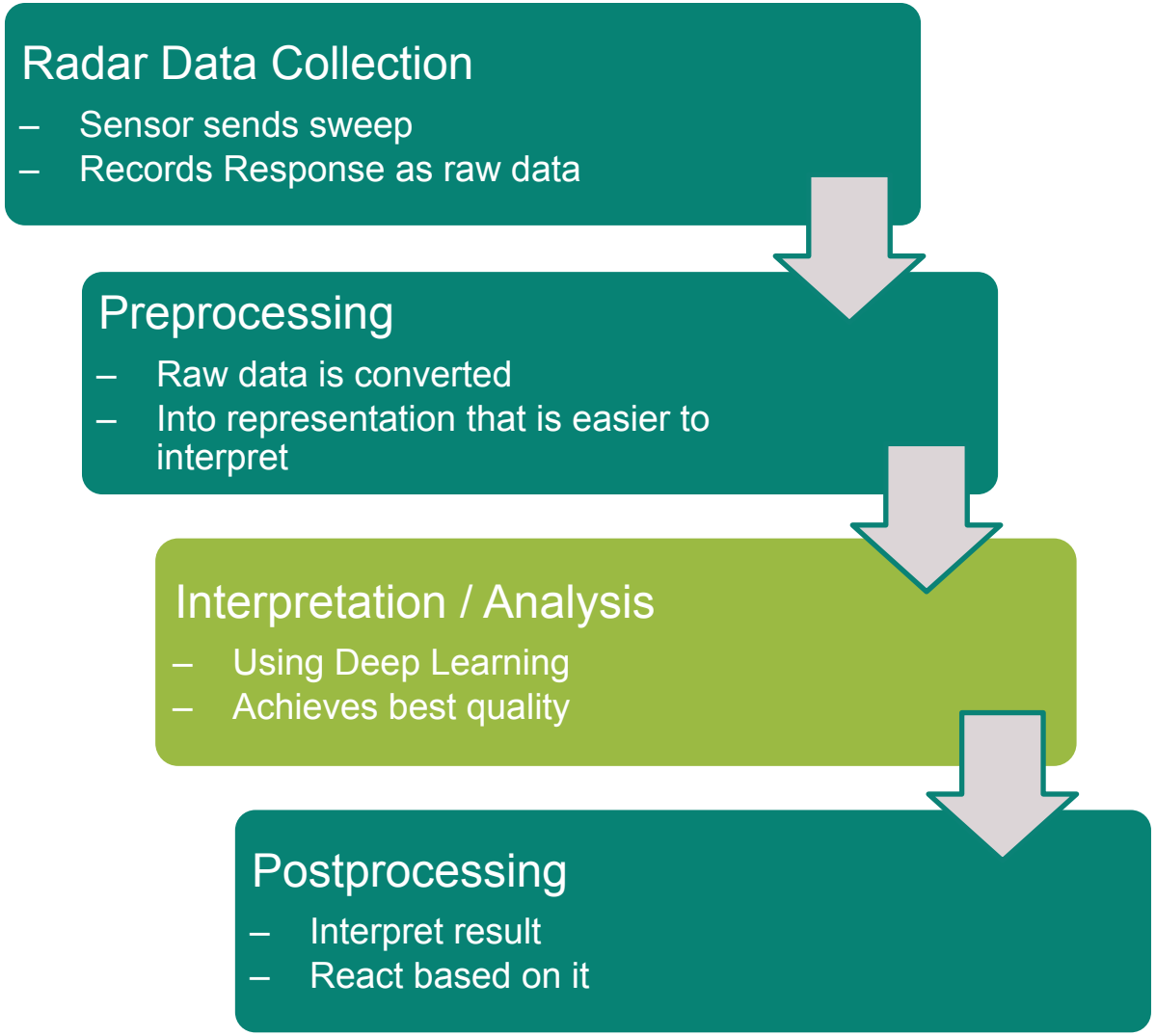


Why Radar Sensors?

Small footprint	– Low Power Consumption – Small Size
Environment independent	– Does not need Lighting Source – Robust against Weather Conditions – Not harmful for Pets
Privacy Preserving	– No Biometric Features – Not Recognition of Person
High Quality Data	– High Resolution – Medium Range – Reconfigurable



Processing Steps



Problem: Processing the Data (locally)

- Radar data must be analyzed to perform the task
  - Preprocessing + Deep Learning Inference
  - Deep Learning enables the best accuracy

- Processing should stay local
  - Maintain independence
  - Maximal flexibility
  - Not all use cases can rely on the presence of more compute resources

- But: “local” = Cortex-M class of devices
  - Needs to perform preprocessing + inference
  - Processing latency needs to be short
  - Power consumption should be as low as possible
  - MCU is limited in compute power

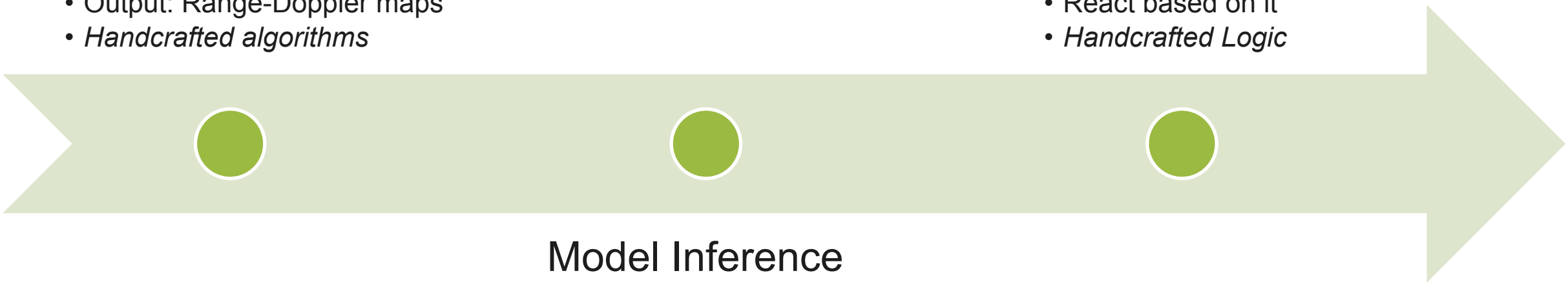
Data Processing

Preprocessing

- Input: raw sensor data
- Output: Range-Doppler maps
- *Handcrafted algorithms*

Postprocessing

- Interpret prediction result
- React based on it
- *Handcrafted Logic*



Model Inference

- Input: Range-Doppler Maps
- Output: Prediction
- *Convolutional Network*

Problem: Processing the Data (locally)

- **One package: Sensor + MCU + Data Processing**
- MCU
  - Cortex-M class device
  - Perform the entire data processing pipeline

Data Processing

- Preprocessing
- Deep Learning Inference
- Postprocessing

- Deep Learning achieves best quality results

Local Execution

- Maximal flexibility
- Maintain independence
- No reliance on additional compute resources

- Allows for coverage of all use cases

Constraints & Requirements

- Users demand short latency
- Low power consumption
- Accurate results

- MCU:
  - Limited compute power
  - Not always a network connection