ACM Multimedia Systems
Smart Camera Systems

Overview Talk

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FAKULTÄT FÜR TECHNISCHE WISSENSCHAFTEN

Institut für Vernetzte und Eingebettete Systeme

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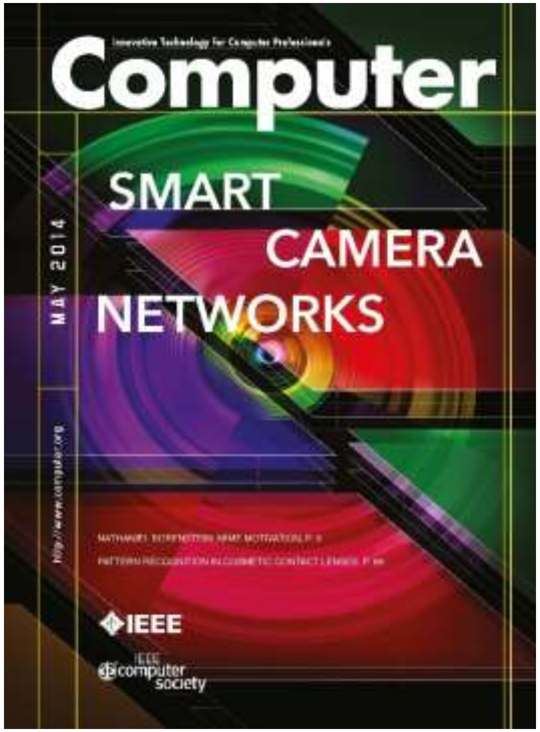
Ubiquitous Cameras

- We are surrounded by billions of cameras in public, private and business spaces
- Various well-known domains
  - Transportation
  - Security
  - Entertainment
  - Mobile
- Cameras serve a purpose and provide some utility
  - Providing documentation/archiving
  - Increasing security
  - Enabling automation
  - Fostering social interaction

Paradigma Shifts in Video Processing

- Towards online/onboard processing
- Towards distributed, in-network analysis
- Towards ad-hoc deployment
  and mobile and open platforms
- Towards user-centric applications

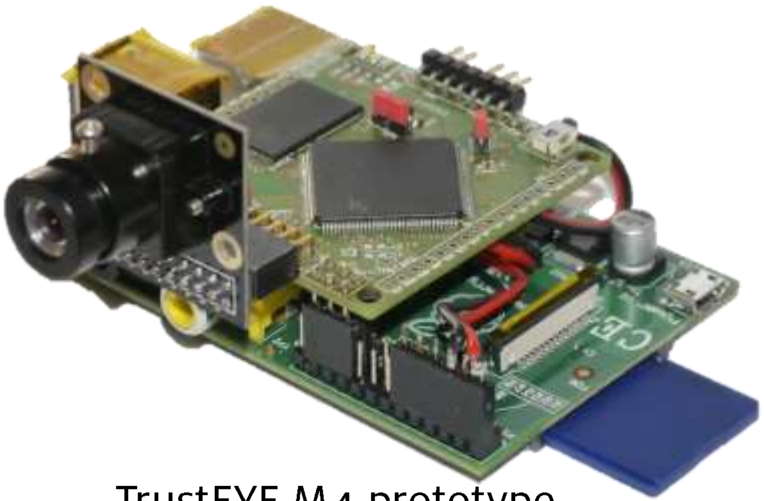


Emergence of Smart Camera Networks !

Smart Cameras as Enabling Technology

- Smart cameras combine
  - sensing,
  - processing and
  - communication

  in a single embedded device



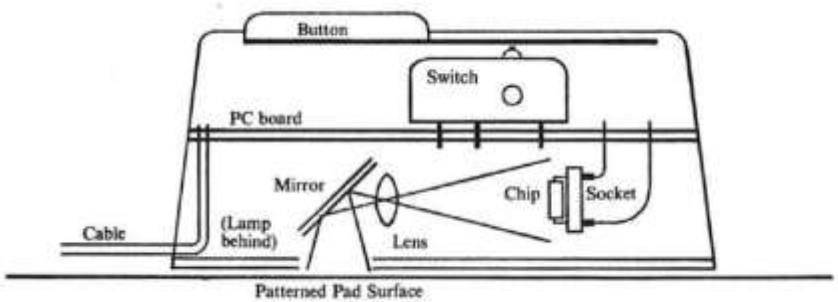
TrustEYE.M4 prototype
on top of RaspberryPI

- perform image and video analysis in real-time closely located at the sensor and transfer only the results
- collaborate with other cameras in the network

[Rinner, Wolf. A Bright Future for Distributed Smart Cameras. Proc. IEEE, 2008]

Some History

- 1981: Xerox optical mouse
  - Single NMOS chip
  - 16 pixel imager and 2D tracking

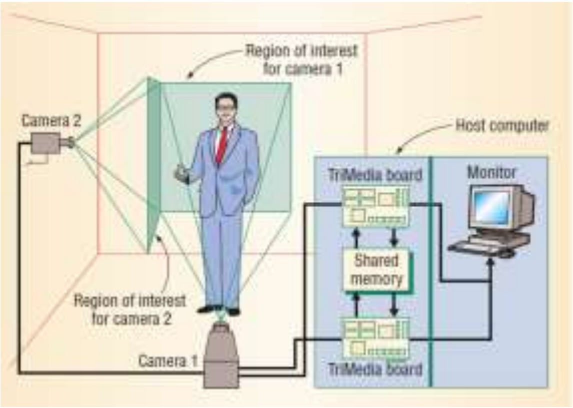


[Lyon. The Optical Mouse, and an Architectural Methodology for Smart Digital Sensors, 1981]

- 1999: CMOS smart camera
  - 250 x 250 pixels @ 10 fps
  - Onchip Canny edge detector

[Moorhead, Binnie. Smart CMOS Camera for Machine Vision Applications, 1999]

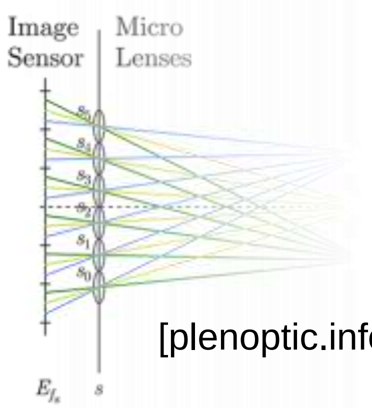
- 2002: Smart multi-camera systems
  - Programmable multi-camera algorithms
  - Implemented on embedded DSP boards



[Wolf et al. Smart Cameras as Embedded Systems. Computer 2002]

Novel Imaging Technology

- Light field sensors are able to capture intensity and direction of light
  - Using micro lens array in front of image sensor,
  - Enables computational photography
  - Commercially available



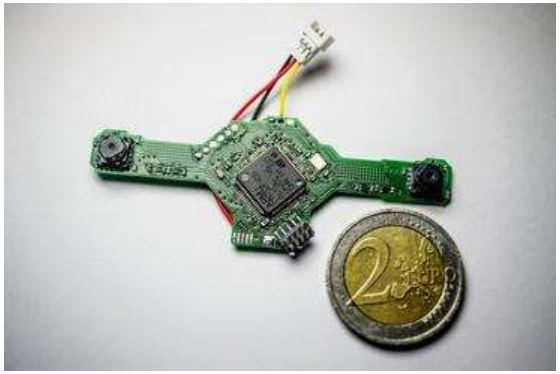
[plenoptic.info]

- Neuromorphic imaging inspired by biology of eye and brain asynchronously samples pixel with
  - Extremly high temporal resolution
  - High dynamic range
  - Event-based image analysis

[chronocam.fr]

Innovative Camera Platforms

- DelFly onboard stereo vision system
  - Multi-sensor (barometer, gyroscope and vision)
  - Robot control and collision avoidance
  - Under strong resource limitations (4 gr)



[delfly.nl]

- Mobile phones for real-time vision processing
  - Highly integrated: sensor(s), processor, display
  - Ubiquitously available platform
  - Various applications: 3D reconstruction, AR

[IKEA]

New Multi Camera Networks

- Multi-view processing
  - Distributed sensing (shared FoV)
  - Centralized analysis with little onboard processing
  - HD, 3D reconstruction, visual effects, …

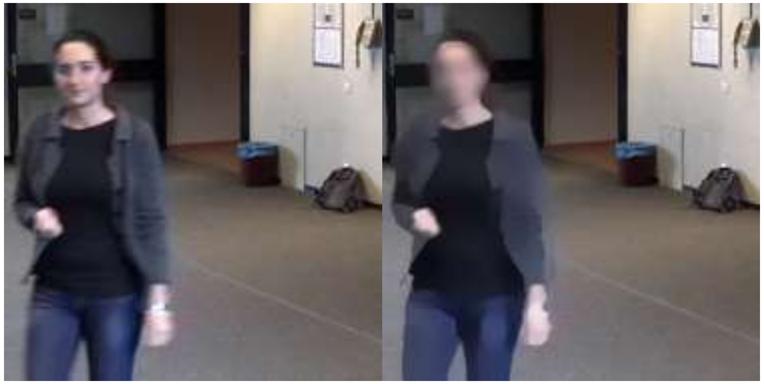
[breezesys.com]

- Distributed camera networks for real-time vision processing
  - Larger environments with non-overlapping FoV
  - Decentralized analysis requires coordination
  - Event notification vs. video streaming
  - Various applications: surveillance, robotics, …

[uav.aau.at]

Agenda

1. Onboard privacy protection in (single) camera
   - Explore tradeoff among utility/protection/resources
   - Embed protection mechanisms close to sensor
2. Self-awareness in camera networks
   - Self-organize tracking in camera networks
   - Learn advantageous strategies of cameras



© MediaEval

© ucf.edu

Topics not covered

1. Multimedia
   – Images as only sensor modality

[wswan.org]

2. Data streaming in networks
   – Deliver events to avoid (raw) data transfers

[streamingmovieguide.org]

Onboard Privacy Protection

Privacy Protection in Images

Source: Wikipedia

Informal Definitions

- Privacy
  - "the processing of personal data regardless of whether such processing is automated or not" (regulated by EU Data protection directive)
- Anonymity
  - "not being identifiable within a set of subjects" ("*k-anonymity*")

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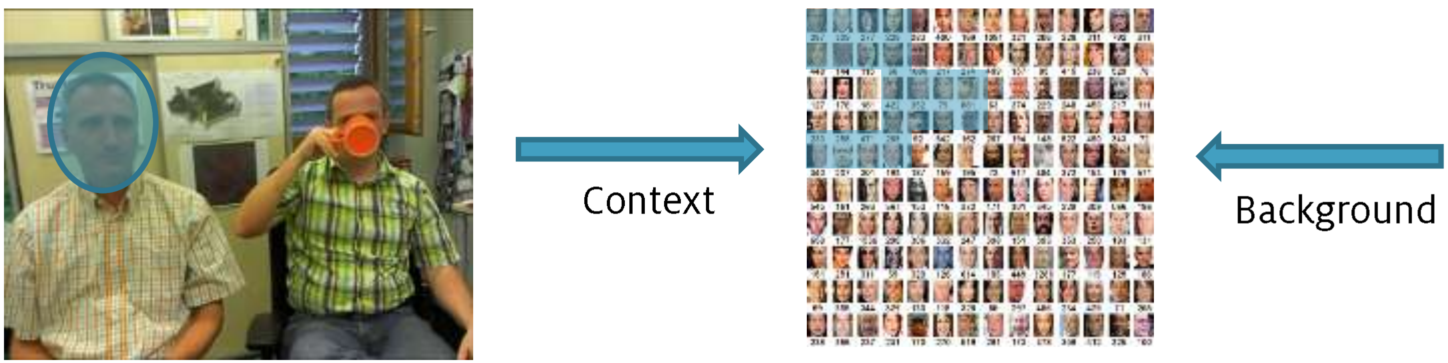
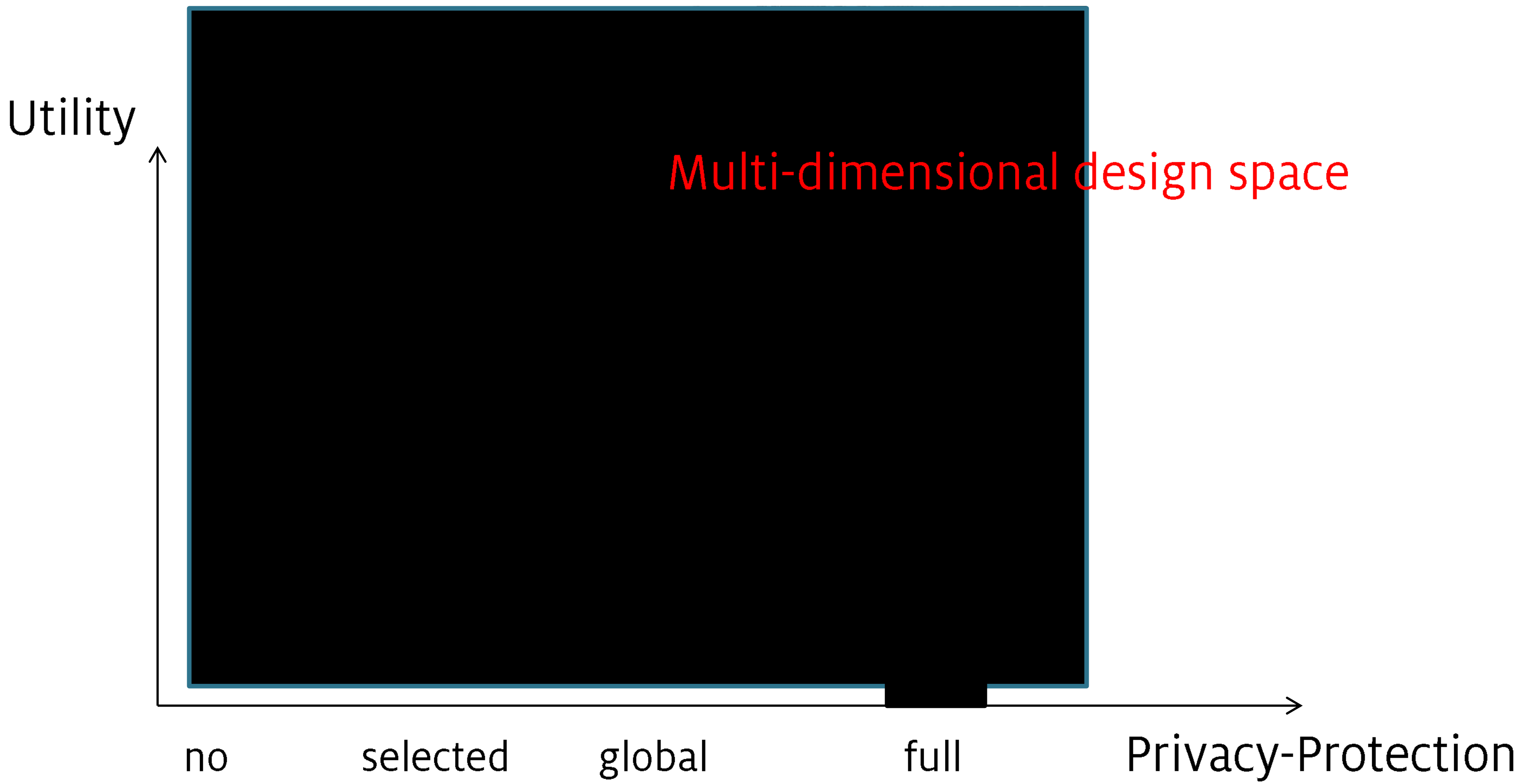


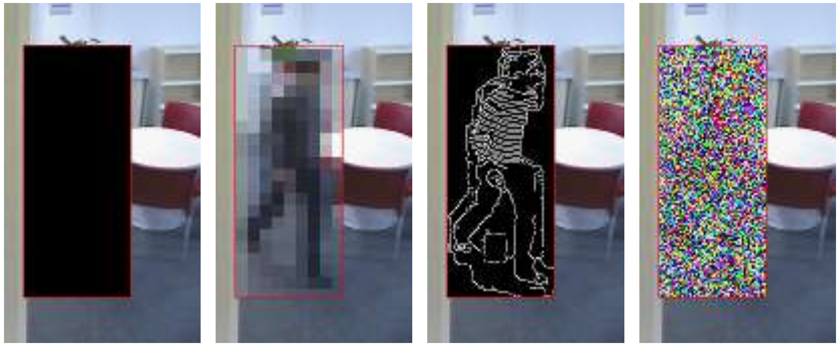
- Utility
  - „ability to exploit information“ (e.g. to detect/count persons)

Utility and Privacy-Protection Tradeoff



Observations and Key Challenges

- Most techniques focus on protecting sensitive regions from unauthorized access
  - Global filters protect entire frame
  - Object-based filters protect ROIs (depend on detection performance)



- No single best privacy protection method, but a large design space along protection/utility/resource dimensions
- Privacy protection goes hand-in-hand with security to provide
  - Non-repudiation
  - Confidentiality

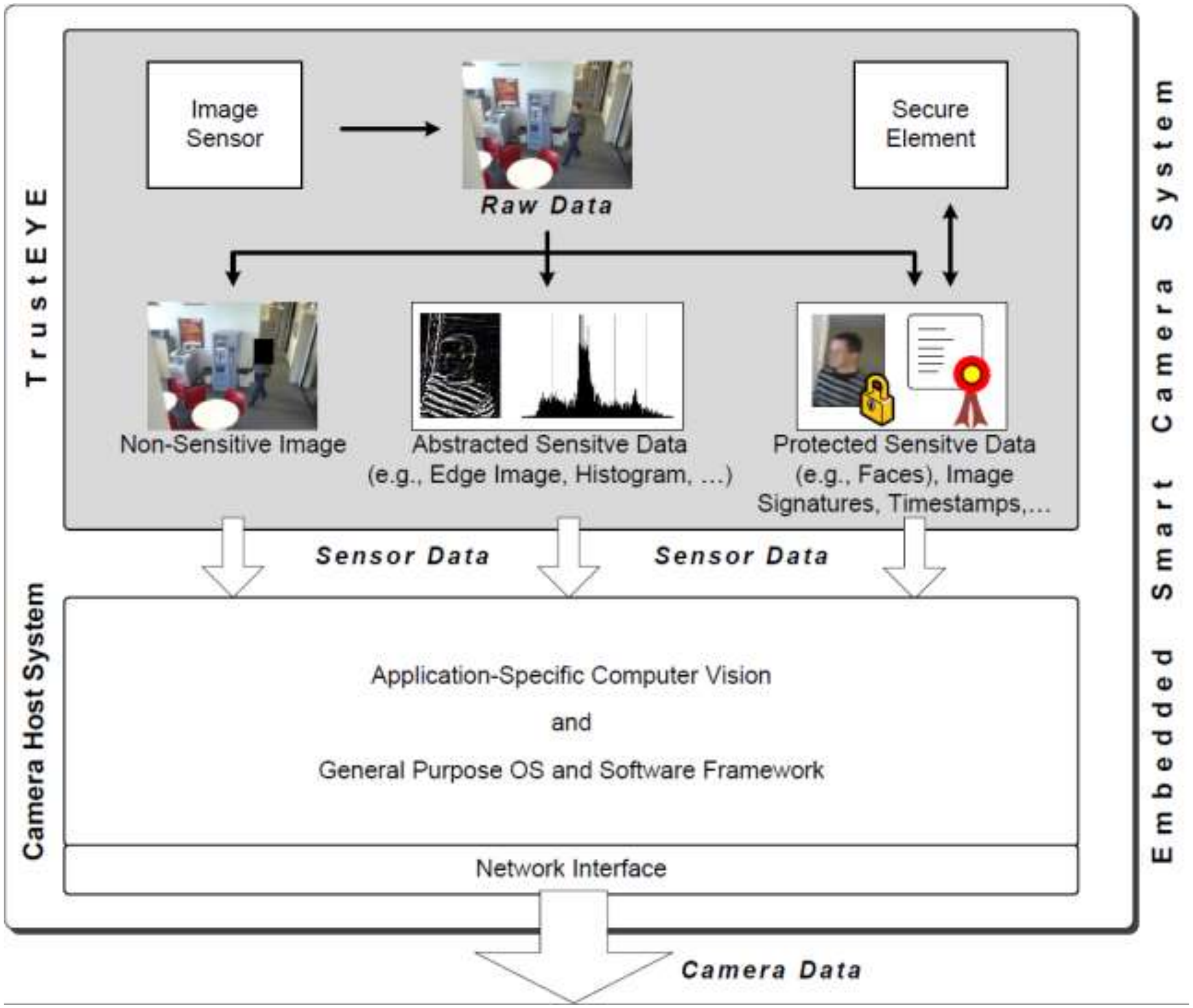
[Winkler, Rinner. Security and Privacy Protection in Visual Sensor Networks: A Survey. ACM Computing Surveys, 2014]

Approach: Trustworthy Sensing (TrustEYE)

- Objective:
  - Protect access to sensor via a trusted component "TrustEYE"
  - Make security and privacy protection an inherent feature of the image sensor
  - Provide resource-efficient and adaptable privacy protection filters
- Benefits:
  - Sensor delivers protected and pre-filtered data
  - Strong separation btw. trusted and untrusted domains
  - Camera software does no longer have to be trustworthy
  - Security can not be bypassed by application developers
  - TrustEYE is anchor for secure inter-camera collaboration

[Winkler, Erdelyi, Rinner. TrustEYE.M4: Protecting the Sensor - not the Camera. In Proc. AVSS 2014]
http://trusteye.aau.at/

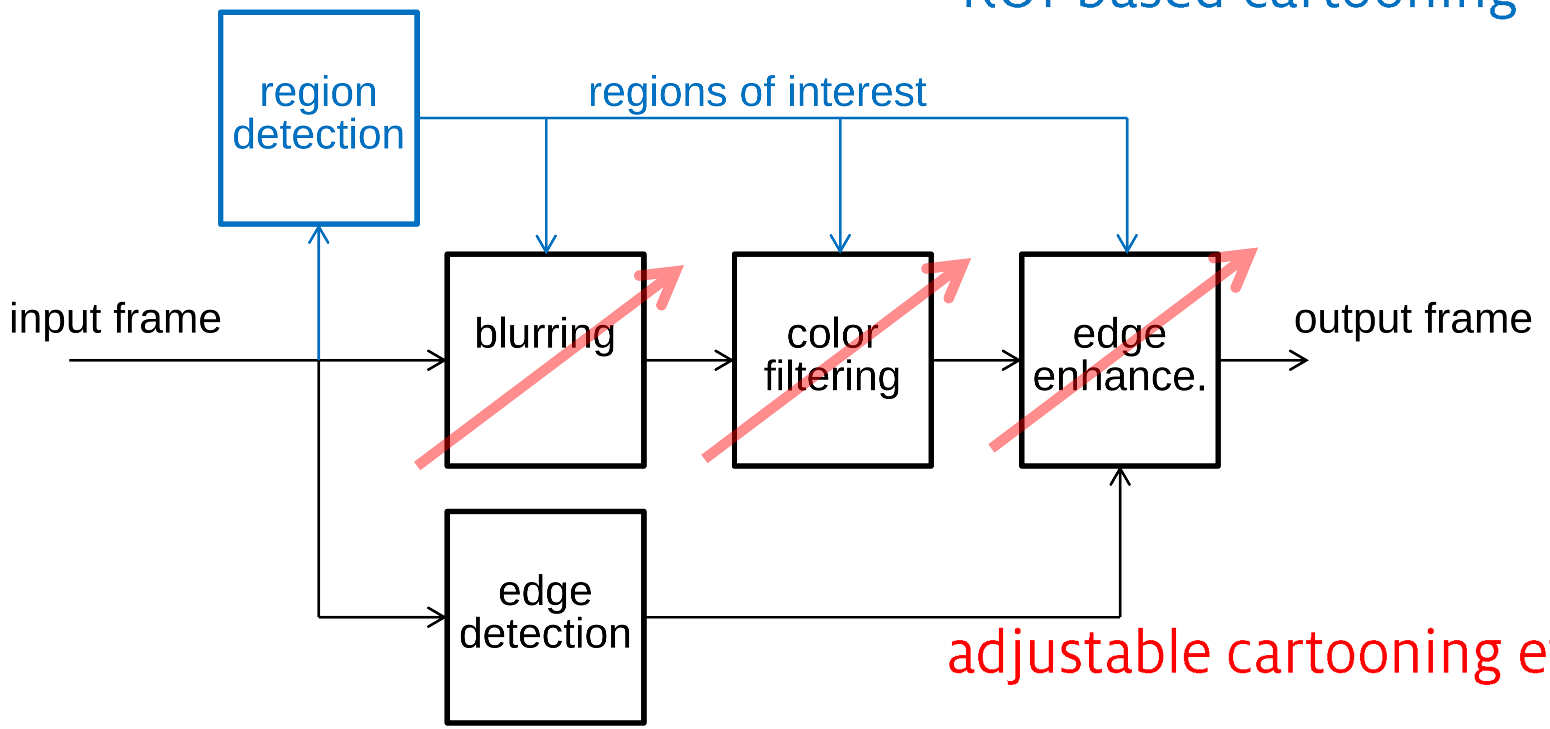
TrustEYE Overview



Privacy Protection by Cartooning

- Abstract parts or entire image by blurring and color filtering
- Cartooning pipeline

ROI-based cartooning



adjustable cartooning effect

- Embed cartooning as privacy feature into smart cameras

ROI-based Cartooning

(c) MediaEval Dataset

Cartooning of detected faces

- Privacy protection depends on performance of region detectors (faces, persons etc.)
- Adapting the filter characteristic beneficial

[Erdelyi et al. Adaptive Cartooning for Privacy Protection in Camera Networks. In Proc. AVSS 2014.]

Adjustable Global Cartooning


original


cartooning (small)


cartooning (std)


cartooning (strong)

(c) MediaEval Dataset

Evaluating Privacy/Utility Tradeoff

- Establish an objective evaluation framework among key dimensions, i.e.,
  - Privacy protection — Identification of objects of interest
  - Utility — Detection/tracking of objects
  - Appearance — Structural similarity with unprotected frame
  - Resource consumption — Achievable frame rate
- Measure the performance using standard CV algorithms with protected videos (and use labeled test data as ground truth)
  - Independently for each frame
  - Measure protection among object's traces

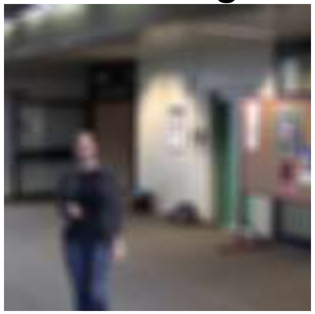
[Erdelyi et al. Adaptive Cartooning for Privacy Protection in Camera Networks. In Proc. IEEE AVSS, 2014]

Comparison of Global Filter Approaches

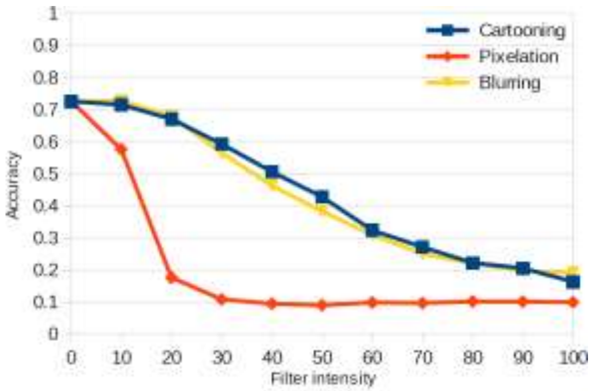
- Performance of standard CV algorithms compared to unprotected video or other protection filters

Cartooning

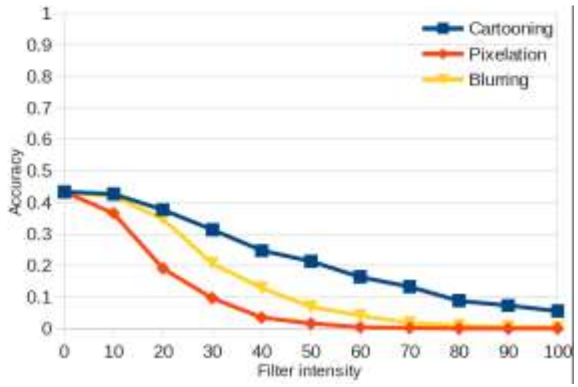
Blurring



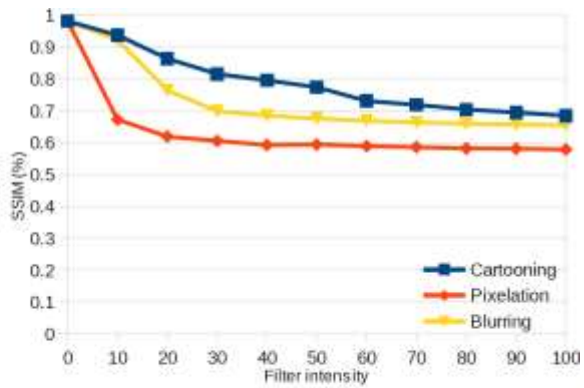
Pixelation



Protection: object re-identification performance

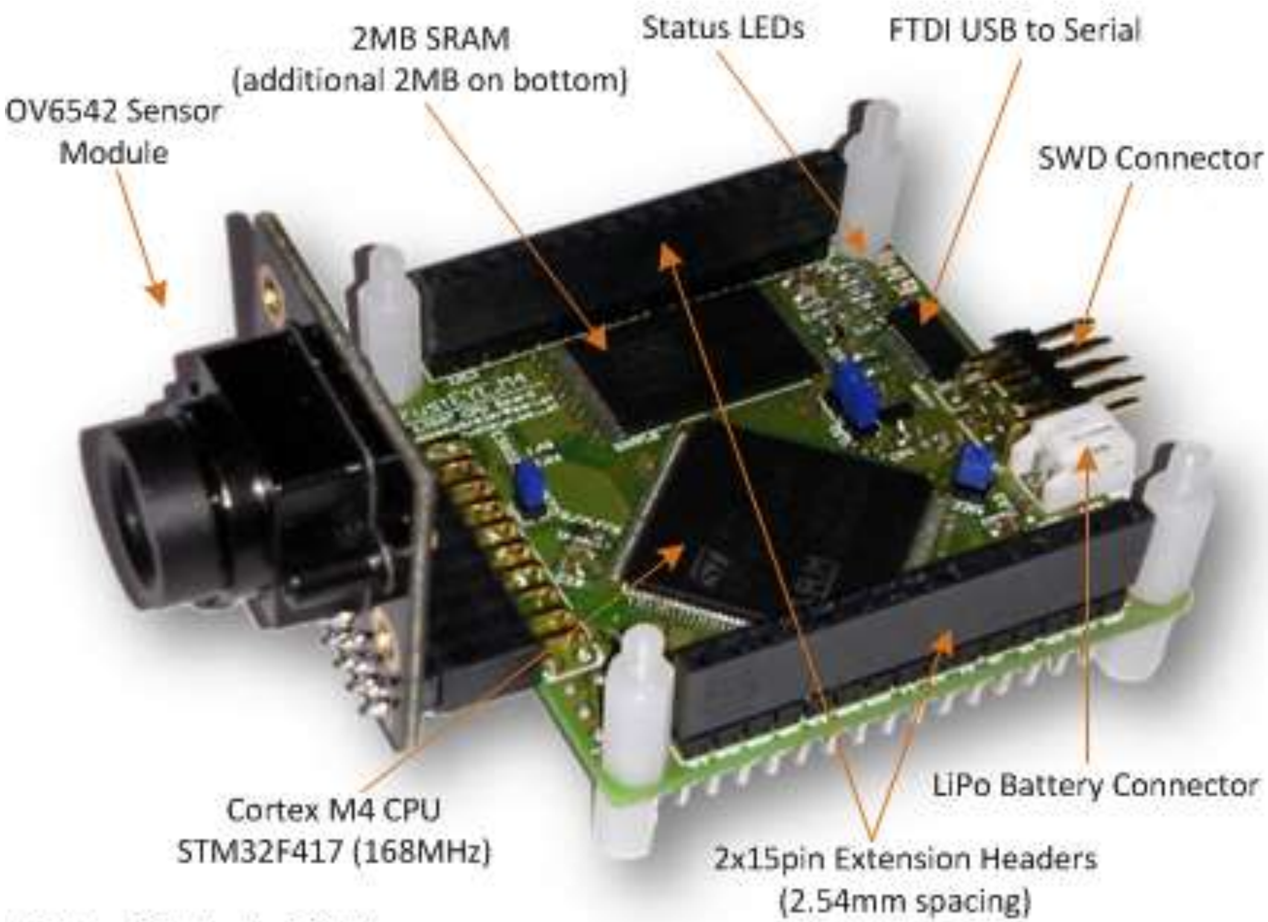


Utility: object detection performance



Appearance: structural similarity index

TrustEYE.M4 Architecture



<u>Bottom Side (not visible):</u>
2MB SRAM, TPM Security IC, Power Management IC
(LiPo Charger), Micro USB Connector, Reset Button

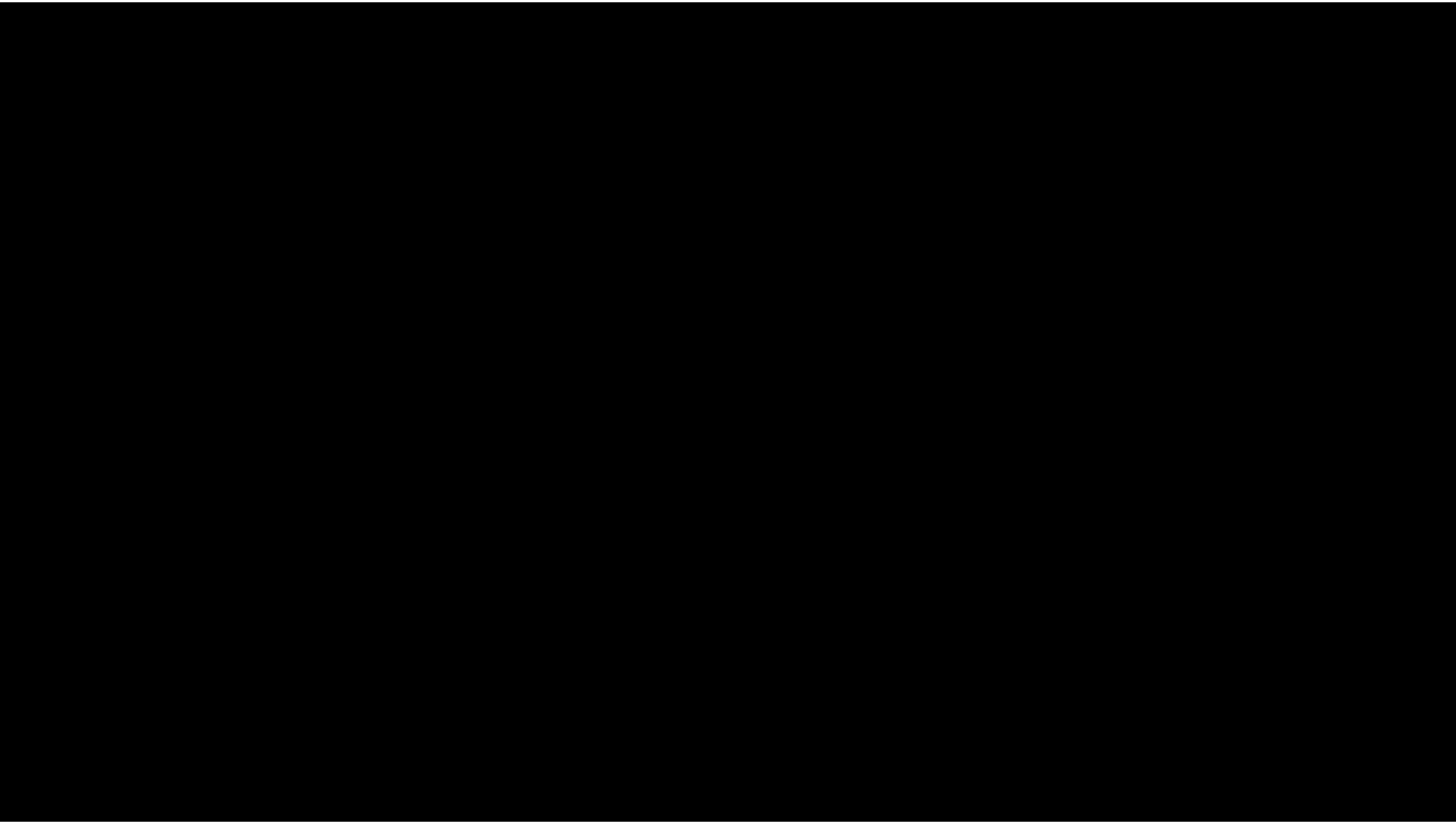
TrustEYE.M4 Prototypes

- Processing board (50x50 mm)
  - ARM Cortex M4 @ 168MHz
  - 4 MB SRAM
  - TPM IC: ST33TPM12SPI via SPI
  - Keil RTX RTOS

- WiFi extension board (50x50 mm)
  - Redpine Signals RS9110-N-11-02
  - 802.11 b/g/n
  - Encryption: WPA2-PSK, WEP
  - Interconnect: SPI bus on 15pin ext. header

- RaspberryPI mounting option
  - Interconnect: SPI bus via dedicated RPI
  - Daterate: 32 Mbit/s

TrustEYE in Action



Self-awareness in Camera Networks

Inspiration from Psychology

- Human self-awareness is a well-studied concept in psychology, cognitive science etc. with many facets
  - „capacity to become the object of own attention“
  - „become aware …experiencing specific mental events“

- Evolved concepts
  - Explicit (objective) vs. implicit (subjective) self-awareness
  - Levels of self-awareness with different capabilities
  - Self-awareness as a property of collective systems

[A. Morin. Levels of Consciousness and Self- Awareness: A Comparison and Integration of Various Neurocognitive Views. Consciousness and Cognition, 2006.]
[U. Neisser. The Roots of Self- Knowledge: Perceiving Self, It, and Thou. Annals of the New York Academy of Sciences, 1997.]

Computational Self-awareness

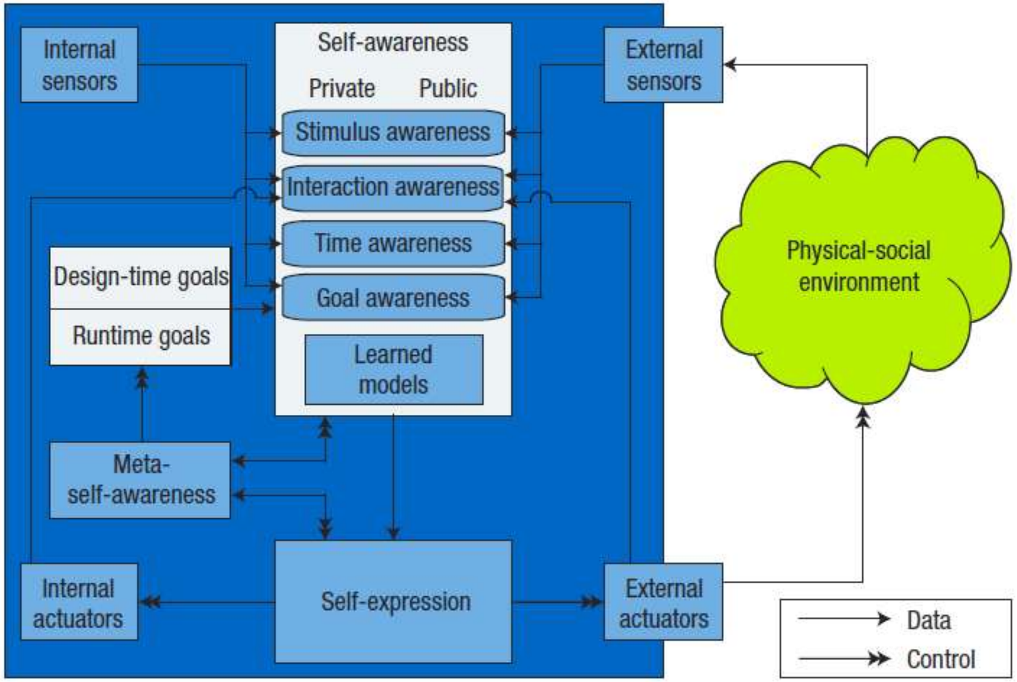
Framework for computational systems that adaptively manage complex tradeoffs at runtime

1. Public and private self-awareness to obtain knowledge on
   - internal phenomena via internal sensors (i.e., internal state)
   - external phenomena via external sensors (i.e., environment)
2. Self-awareness levels
   - different capabilities for obtaining and exploiting knowledge
   - stimulus-, interaction-, time-, goal- and meta-self-awareness
3. Collective and emergent self-awareness
   - founded on local capabilities

[Lewis et al. Architectural Aspects of Self-Aware and Self-Expressive Computing Systems: From Psychology to Engineering. IEEE Computer, 2015]

Reference Architecture

- Computational self-awareness as process(es) with



models of system knoweldge

ways to update models

self-expression (behavior based on self-awareness)

[Lewis et al. [Architectural Aspects of Self-Aware and Self-Expressive Computing Systems: From Psychology to Engineering](). IEEE Computer, 2015]

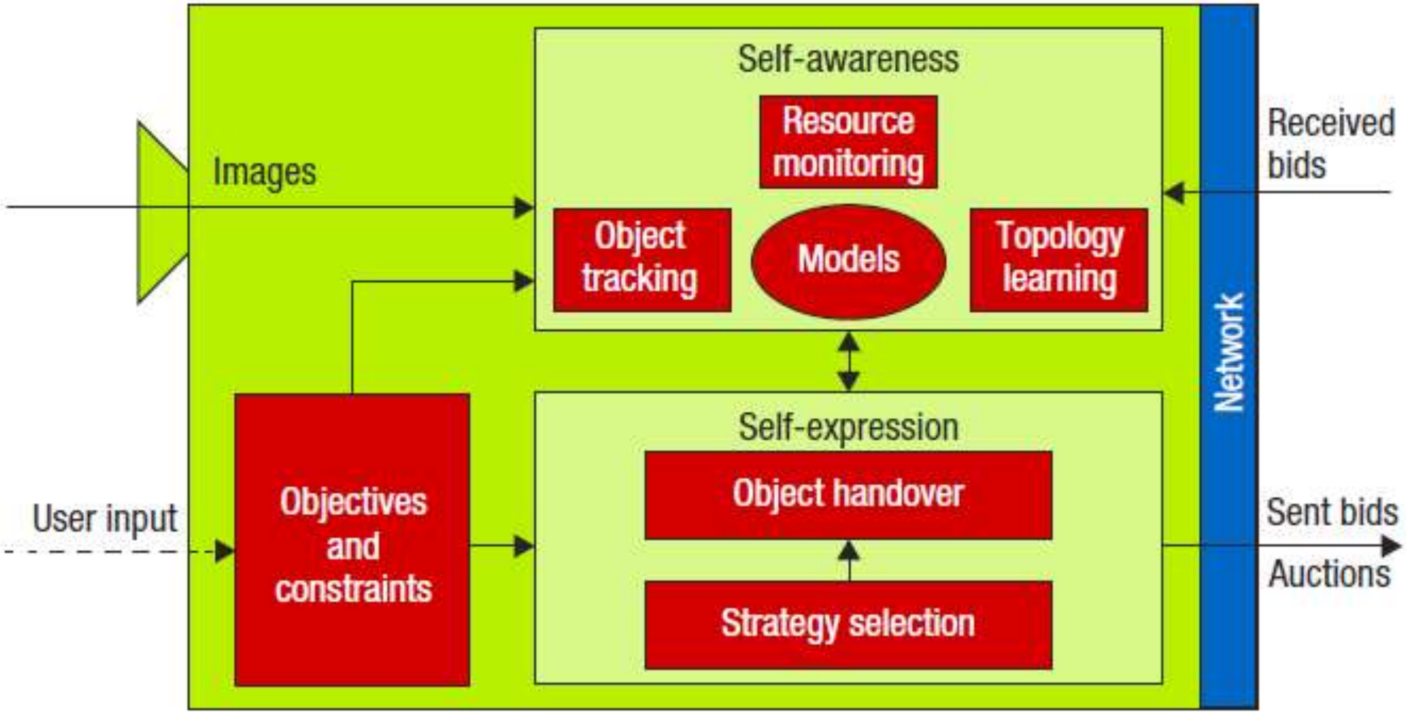
Self-aware Camera Network

- Perform autonomous, decentralized and resource-aware network-wide analysis

- Demonstrate autonomous multi-object tracking in camera network
  - Exploit single camera object detector & tracker
  - Perform camera handover
  - Learn camera topology
- Key decisions for each camera
  - When to track an object within its FOV
  - When to initiate a handover
  - Whom to handover

Self-aware Camera Node

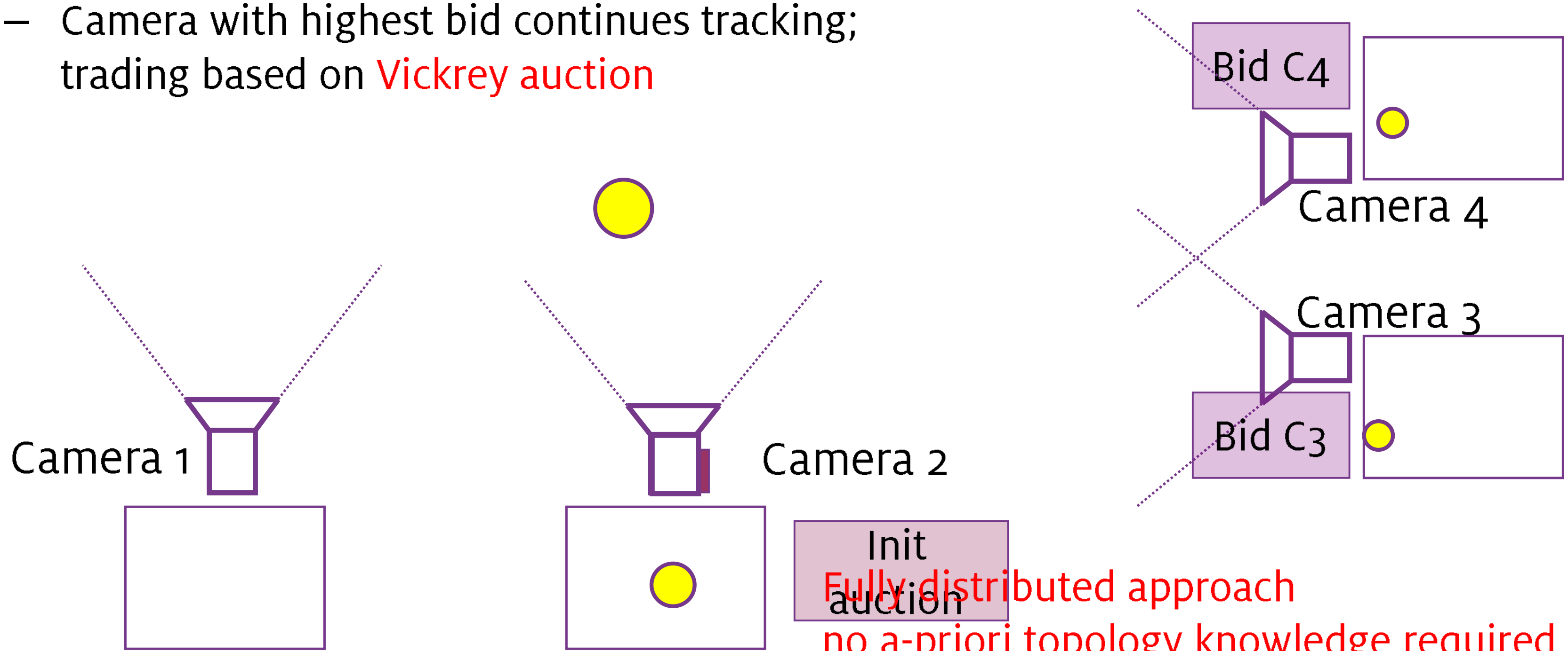
- Design following computational self-awareness



[Rinner et al. Self-aware and Self-expressive Camera Networks. IEEE Computer, 2015]

Virtual Market-based Handover

- Initialize auctions for exchanging tracking responsibilities
  - Cameras act as self-interested agents, i.e., maximize their own utility
  - Selling camera (where object is leaving FOV) opens the auction
  - Other cameras return bids with price corresponding to "tracking" confidence
  - Camera with highest bid continues tracking;
    trading based on Vickrey auction



Fully distributed approach
no a-priori topology knowledge required

Camera Control

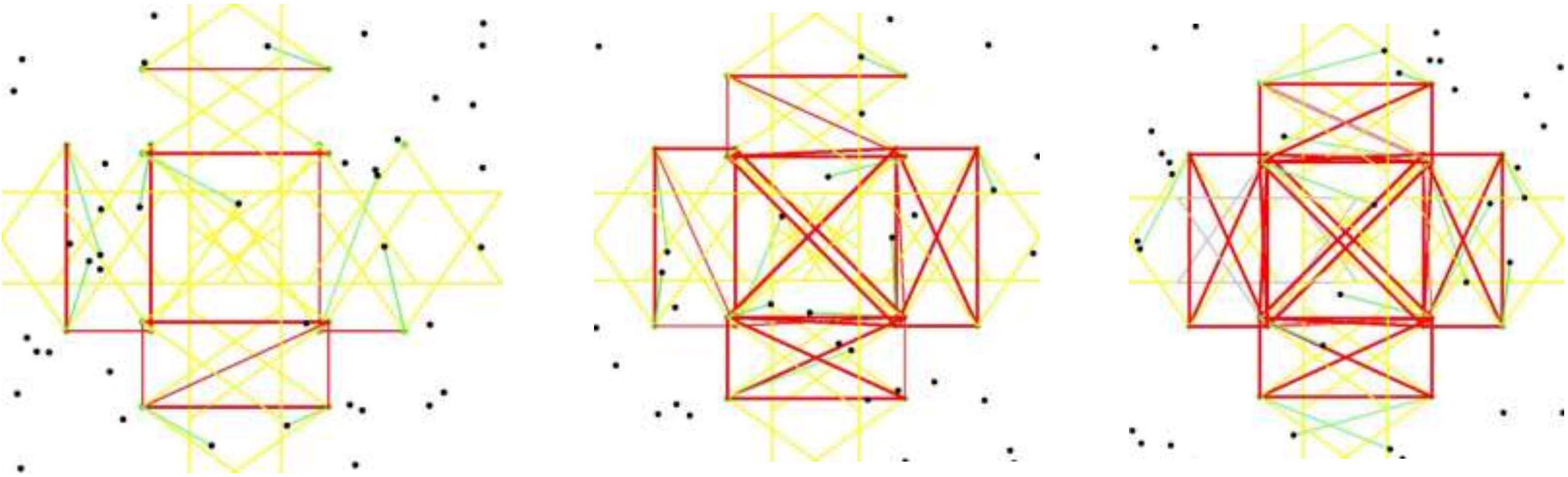
- Each camera acts as agent maximizing its utility function

$$U_i(O_i) = \sum_{j \in O_i} [c_j \cdot v_j \cdot \Phi_i(j)] - p + r$$

- Local decisions
  - When to initiate an auction (at regular intervals or specific events)
  - Whom to invite (all vs. neighboring cameras)
  - When to trade (depends on valuation of objects in FOV)
- Learn neighborhood relations with trading behavior (“pheromones”)
  - Strengthen links to buying cameras
  - Weaken links over time

Learn Neighborhood Relationships

- Gaining knowledge about the network topology (vision graph) by exploiting the trading activities
- Temporal evolution of the vision graph



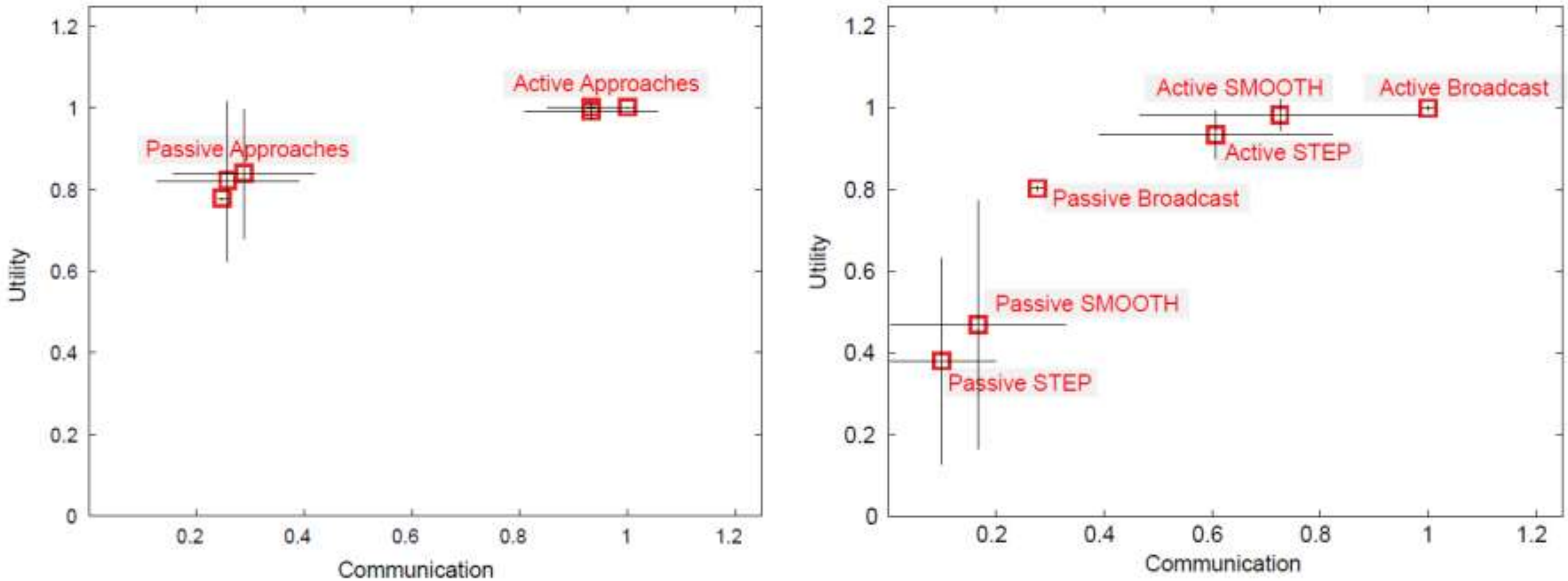
Six Camera Strategies

- Auction initiation
  - “Active”: at regular intervals (at each frame)
  - “Passive”: only when object is about to leave the FOV
- Auction invitation
  - “Broadcast”: to all cameras
  - “Smooth”: probabilistic proportional to link strength
  - “Step”: to cameras with link strengths above threshold (and rest with low probability)

- Selected strategy influences network performance (utility) and communication effort

Tracking Performance

- Tradeoff between utility and communication effort



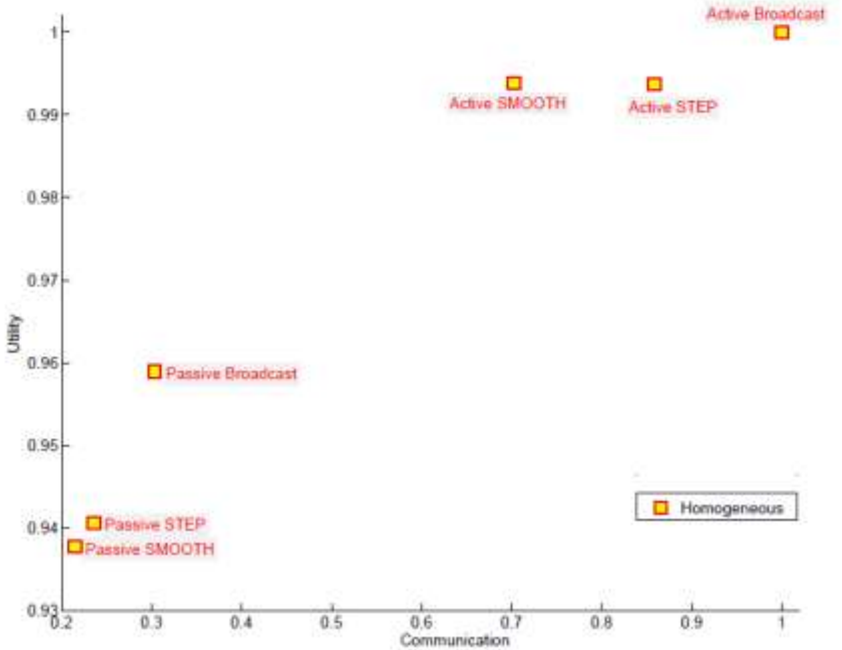
Scenario 1 (5 cameras, few objects) Scenario 2 (15 cameras, many objects)

- Emerging Pareto front

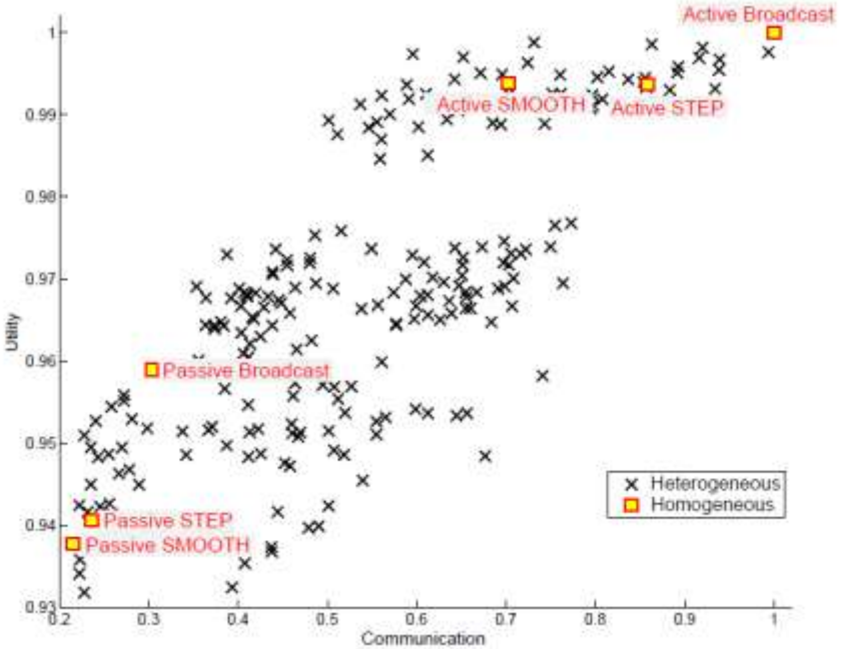
[Esterle et al. Socio-Economic Vision Graph Generation and Handover in Distributed Smart Camera Networks. ACM Trans. Sensor Networks. 10(2), 2014]

Assigning Strategies to Cameras

- Identical strategy for all cameras may not achieve best result



Homogeneous strategies (3 cameras)



Heterogeneous strategies (3 cameras)

- Strategy depends on various parameters (FOV, neighbors, scene …)
  - Let cameras learn their best strategy

Decentralized Multi-Agent Learning

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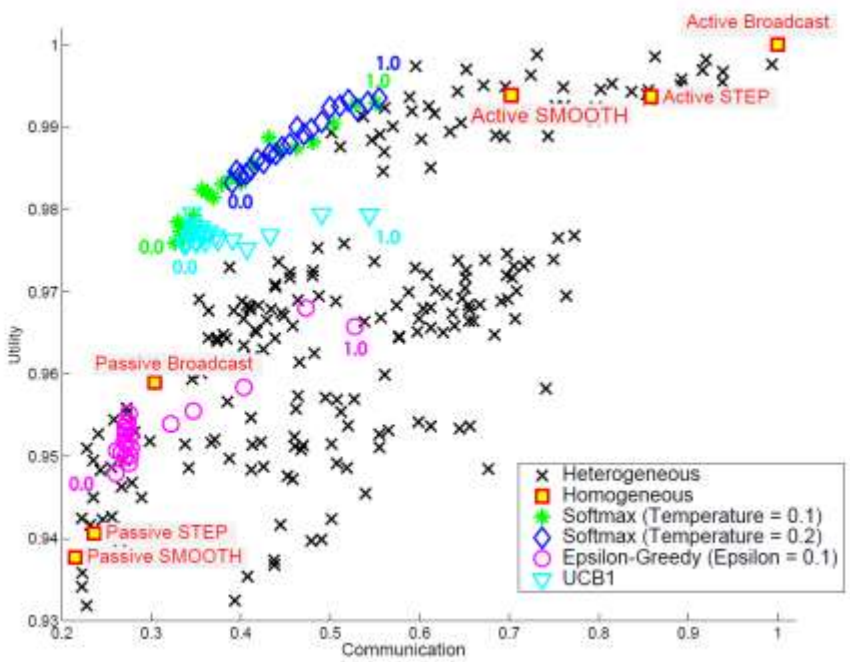
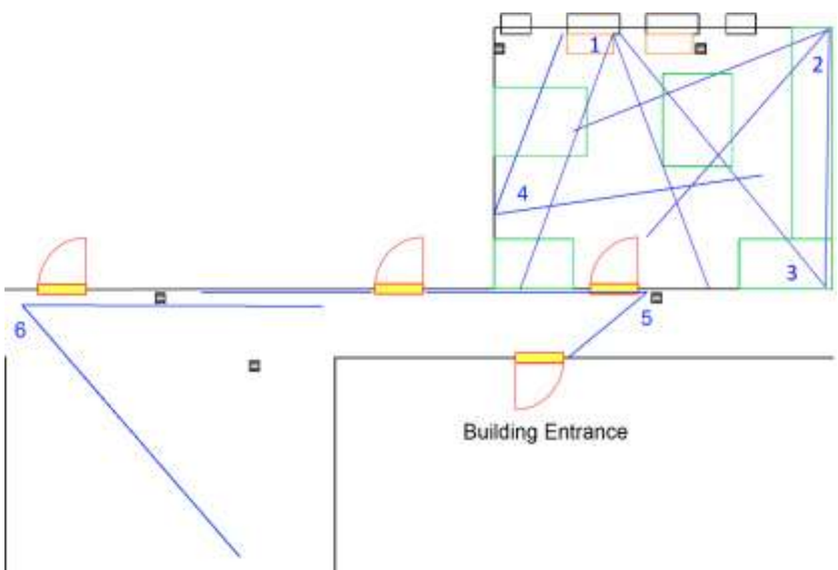
- Exploit bandit solver framework to maximize global performance
  - Co-dependency among agents' performance
  - Complex relationship between local reward global performance

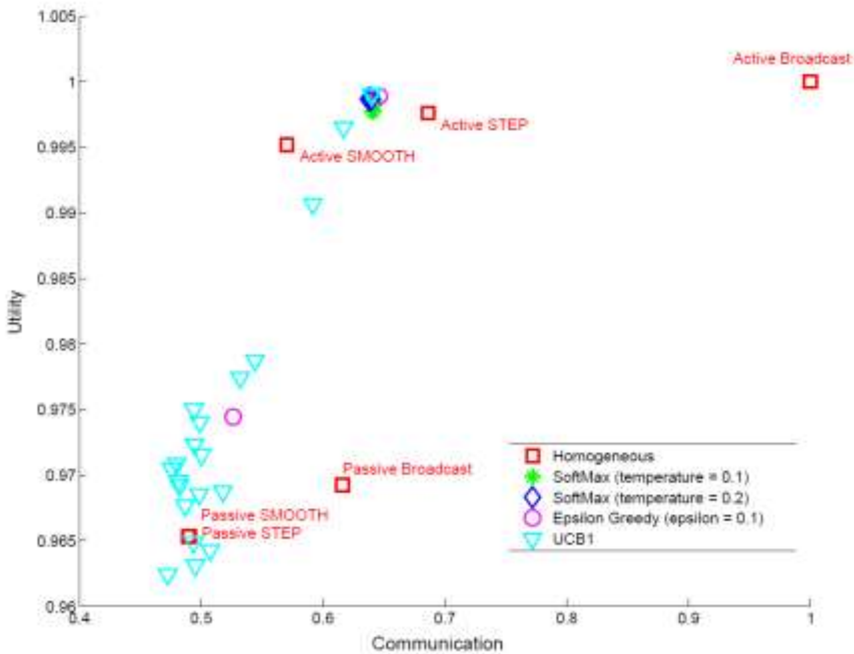


[Lewis et al. [Static, Dynamic and Adaptive Heterogeneity in Socio-Economic Distributed Smart Camera Networks](). ACM Trans. Autonom. Adapt. Syst. 2015]

Multi-camera Experiment

- Indoor demonstrator with 6 cameras tracking 6 persons
- Each camera performs
  - Color-based tracking
  - Fixed or adaptive handover strategies (bandit solvers)
  - Exchange of color histograms for person re-identification





Conclusion

- Smart cameras process video data onboard and collaborate autonomously within the network
- Our cartooning approach protects image data "at the sensor" but stills provides reasonable utility with low resource usage
- We apply socio-economic techniques to learn control strategies for autonomous multi-camera tracking
  - Global configurations emerge from local decision using local metrics
  - Adaptive strategies extend Pareto front of best static configurations
- Techniques applicable to various decentralized networked systems (e.g., Internet of Things)

Acknowledgements & Further Information

Pervasive Computing group

Institute of Networked and Embedded Systems

http://nes.aau.at

http://bernhardrinner.com

Funding support

- KWF/FWF "Trustworthy Sensing and Cooperation in Visual Sensor Networks"
- FP7 FET "Engineering Proprioception in Computing Systems"

Upcoming book

Lewis, Platzner, Rinner, Torresen, Yao. Self-aware Computing Systems: An Engineering Approach. Springer. 2016