Chapter 13
Self-aware Object Tracking in Multi-Camera Networks

Lukas Esterle, Jennifer Simonjan, Georg Nebehay, Roman Pflugfelder, Gustavo Fernández Domínguez, and Bernhard Rinner

Abstract This chapter discusses another example of self-aware and self-expressive systems: a multi-camera network for object tracking. It provides a detailed description of how the concepts of self-awareness and self-expression can be implemented in a real network of smart cameras. In contrast to traditional cameras, smart cameras are able to perform image analysis on-board and collaborate with other cameras in order to analyse the dynamic behaviour of objects in partly unknown environments. Self-aware and self-expressive smart cameras are even able to reason about their current state and to adapt their algorithms in response to changes in their environment and the network. Self-awareness and self-expression allow them to manage the trade-off among performance, flexibility, resources and reliability during runtime. Due to the uncertainties and dynamics in the network a fixed configuration of the cameras is infeasible. We adopt the concepts of self-awareness and self-expression for autonomous monitoring of the state and progress of each camera in the network and adapt its behaviour to changing conditions. In this chapter we focus on describing the building blocks for self-aware camera networks and demonstrate the key characteristics in a multi-camera object tracking application both in simulation and in a real camera network. The proposed application implements the goal sharing

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with time-awareness capability pattern, including meta-self-awareness capabilities as discussed in Chapter 5. Furthermore, the distributed camera network employs the middleware system described in Chapter 11 to facilitate distributed coordination of tracking responsibilities. Moreover, the application uses socially inspired techniques and mechanisms discussed in Chapter 7.

13.1 Smart Camera Networks

Recent advances in technology make cameras almost omnipresent in our everyday life. Cameras are widely used for applications in security, disaster response, environmental monitoring and smart environments, among others. *Smart cameras* have emerged recently by bringing together advances in computer vision, embedded computing, image sensors and networks [415, 341]. They provide image sensing, processing, storage and communication capabilities onboard an embedded device. Smart cameras gained acceptance due to various reasons, including the low system costs, the ability to avoid network loads and the wide range of possible application scenarios. Soon enough, single smart cameras were connected to distributed smart camera networks. They are real-time, distributed, embedded systems that perform computer vision tasks using multiple cameras [45, 342, 336]. Compared to a network of traditional cameras, smart cameras offer the benefit that raw data do not have to be transmitted via the network. These raw data are processed on the sensor platform and necessary results are transmitted. As each camera has reasonable computing and communication capabilities, such a network of smart cameras can be treated as a distributed system for image processing.

In order to allow useful in-network processing of captured imagery, smart camera networks have to deal with various challenges. These challenges vary from highly dynamic behaviour of objects over partially unknown environments to required cooperation with neighbouring cameras on demand. To enable future cameras to deal with these challenges without human interaction, they are required to achieve advanced levels of autonomous behaviour to adapt themselves at runtime and learn appropriate behaviours for changing conditions. A particular challenge is to manage the trade-off of conflicting objectives such as high performance, low resource consumption and high reliability. Not knowing possible changes due to dynamics in the objects' behaviour, the environment or the network itself does not allow a fixed configuration [348]. An adaptive approach only allows a system to change based on predefined options and again only based on expected and foreseen trade-offs.

In this chapter we adopt the concepts of *self-awareness* and *self-expression* as a successful alternative to fixed configurations. We translate these concepts to computational analogies and apply them to smart camera networks [340]. As introduced in Chapter 12, self-awareness refers to the ability of a system to obtain and maintain knowledge about its state, behaviour and progress, enabling self-expression, the generation of autonomous behaviour based on such self-awareness. Combining both self-awareness and self-expression allows for adaptation of a camera's behaviour to changing conditions in an effective and autonomous manner. We therefore implement the reference architecture using the goal sharing pattern. We enhance this pattern with meta-self-aware capabilities to improve our application even further. The fundamental building blocks to achieve self-awareness and self-expression in a camera are effective sensing of the environment, learning models of the camera's state and context during runtime as well as decentralised decision making. The building blocks and their interactions are explained in this chapter in order to build a computationally self-aware and self-expressive camera network. Its features and capabilities are demonstrated with a distributed multi-camera tracking application as an example.

13.2 Object Tracking

Object tracking is an important topic and an extensively investigated subject within the field of computer vision. Research of object tracking algorithms has generated great interest in the computer vision community due to the many fields of application such as automated surveillance, security, object indexing and retrieval, human computer interaction, transportation and activity recognition. Object tracking can be classified as an intermediate-level computer vision task. Low-level information, such as edge segments or corner points, is used to build the desired trajectory in order to provide it for high-level tasks such as object retrieval or activity recognition. Basically, the goal of a tracking task is to recover the motion paths or trajectories of objects using detected object locations, such that each recovered trajectory represents the motion of a single object. Given an object i in frame t (noted as O_i^t) and a set of 'n' candidate objects in frame $(t+1)$ O_k^{t+1} (where $k = 1,...,n$), the tracking problem consists of selecting an object j in frame $(t+1)$, i.e., O_j^{t+1}, from among all 'n' objects which best matches with object O_i^t. The term object refers to image objects and the best matching is specified by some distance measure.

Unfortunately, the captured visual data is usually contaminated with noise, and missing observations increase the complexity of the tracking task. Objects can appear in different orientations, rotations and shapes depending on how they are oriented towards the camera. Occlusions can occur any time while reliable detections are still needed. Changing lighting conditions may appear in many environments and add another challenge to the tracking algorithms. Therefore, advanced techniques for data association and state estimation are necessary to provide robustness in the generation of the objects' trajectories, i.e., to succeed in the tracking task. Tracking algorithms can be classified according to different criteria, including the type of information the algorithms extract and use, the extraction method, and the matching approach (e.g., deterministic or stochastic). We refer the interested reader to [421] for a survey of tracking algorithms, to [392] for video tracking and to [184] for visual surveillance tracking.

In a multi-camera network the goal is to detect, localise and track moving objects such as pedestrians or vehicles within the fields of view (FOVs) of all cameras throughout the whole network. Besides the aforementioned difficulties, multi-camera tracking poses additional challenges due to dynamics of the environment, uncertainties of camera pose and network topology. In comparison to tracking objects in a single camera, multi-camera tracking requires the cooperation of the cameras to delegate tracking responsibilities. The use of epipolar geometry to fuse the object locations is useful when cameras have overlapping FOVs [209, 319]. However, in many scenarios and applications, cameras do not have overlapping FOVs. In such situations, assumptions about the path followed by the object or its speed [185, 214, 200], use of a motion model [320], assumptions about geometry of the scene [253] or a combination of learning the spatial links between cameras, movement of the object and colour information [298] are useful to track objects successfully.

13.3 Multi-camera Tracking Coordination

Transferring tracking from single cameras to a network of multiple cameras requires coordination of the tracking responsibility. Coordinating this responsibility for tracking an object among multiple cameras is a fundamental issue in online multi-camera tracking. A particular challenge is maintaining the association of objects when they move among cameras, i.e., to re-identify tracked objects among multiple cameras [381]. Once a desired object to be tracked is identified, the camera network has to decide by itself how to track this object through the network whenever this object is present in the observed scenario.

In centralised coordination, the cameras send the traces of the objects within their FOV to a central node which then selects the "best" trace. Various approaches have been proposed to coordinate tracking responsibilities in camera networks [199, 77, 245]. A central component for coordination of tracking responsibilities introduces benefits and drawbacks. On the downside, gathering all information on a single entity adds significant communication overhead and computational load on a single component. Furthermore, a centralised approach limits scalability and introduces a single point of failure, reducing the applicability of this approach in large camera networks. On the upside, a centralised approach may achieve a better tracking performance due to the availability of complete tracking and state information from all sensors in a single node. A comprehensive analysis of the state of the art is given in [322, 280].

In distributed coordination each camera decides on its own when and to whom to hand over the tracking responsibility. This distributes the computational load to the cameras in the network and reduces the communication overhead by avoiding transmitting full state information of all cameras. This makes the network not only highly scalable but also quite robust to failure of single cameras or even to changes in network topology caused by dynamically adding cameras. Various approaches for distributed coordination without centralised control have been presented in the literature [118, 328, 128]. Deriving the handover decision based on possibly incomplete, local information and with a camera's limited resources is still a fundamental challenge in distributed coordination.

In the following we summarise how self-aware and self-expressive approaches are used in order to enable a network of smart cameras to coordinate tracking responsibilities autonomously and efficiently among each other.

13.4 Self-aware and Self-expressive Building Blocks

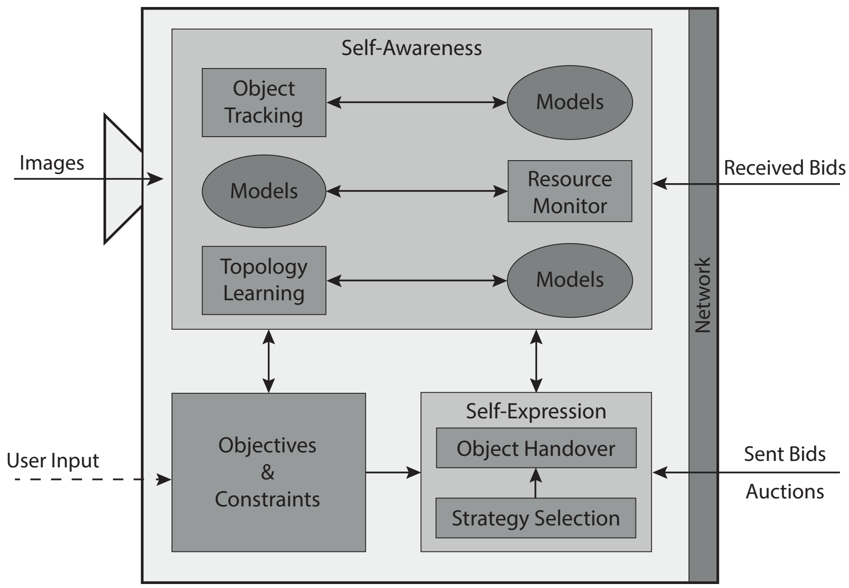


Fig. 13.1 The architecture of a self-aware and self-expressive camera node composed by six building blocks

To endow a camera network with self-awareness and self-expression, dedicated self-aware and self-expressive building blocks are implemented in the individual camera nodes. The different building blocks are able to interact with blocks locally on each camera as well as with other blocks in the network on remote cameras. The blocks depicted in Figure 13.1 aim for a generic and flexible design and implement architectural self-aware and self-expressive patterns as discussed in Chapter 5. Self-aware building blocks, such as *object tracking*, *resource monitoring*, and *topology learning*, are able to monitor its state and behaviour. Utilising online learning techniques allows them to maintain models of their states and the respective behaviour rather than rely on predefined knowledge and rules. The generated models are then used in the self-expressive building blocks (i.e., *object handover* and *strategy selection*) to steer the behaviour of the entire system. The *objectives & constraints* block represents the camera's goals and resource constraints. Both highly influence the other blocks and hence the behaviour and interaction of each individual camera in the network.

The aggregation of individual camera nodes allows the composition of a truly self-aware and self-expressive decentralised camera network. As our employed embedded camera platforms are rather resource-constrained, we focussed the design of each individual building block on resource awareness. Thus, while each building block can be utilising a diverse number of algorithms from computer vision, online learning, distributed coordination and decision making for their implementation, all building blocks have to be able to execute in real time.

In an iterative design process, we initially implemented the interaction awareness pattern in order to allow the cameras to learn about their neighbouring cameras. This allowed the individual cameras to coordinate tracking responsibilities among local neighbouring cameras rather than the entire network. In the next step, we introduced time awareness and enabled each individual camera to also "unlearn" previous learnt information. This becomes important in case the network changes during runtime. In the final step for this application, we introduced meta-self-aware capabilities. These capabilities allow the cameras to trade off exploration, identifying local changes in the network, and exploitation, using the previously learnt information in order to optimise coordination of tracking responsibilities.

13.4.1 Object Tracking

The *object tracking* (OT) building block of each camera is responsible for acquiring images, detecting objects and tracking them within the camera's FOV. Additionally, the OT block transmits images and tracking results to other interested components in the system (for example, the user interface), and if necessary it can update the model of the object during runtime. Identifying the model within the FOV of a camera relates to *private self-awareness* whereas creating and adapting the model of an object corresponds to the *model* in our reference architecture (cf. Chapter 3). The tracking process is described as semi-automatic because the user has to select the desired object to be tracked. After initialising the process, the computer vision tasks run automatically.

The implementation of this self-aware and self-expressive camera network application has been performed in multiple iterations. While the initial version was limited to tracking a single object within the camera network, the final version was capable of simultaneously tracking three people on a network of six smart cameras. The camera network employs appearance-based tracking without using temporal information from previous frames. As soon as the object has been identified within the FOV of the camera, the OT starts tracking the object. By doing so, the OT can adapt the visual representation of the object and improve the internal model if this is desired. This simple approach achieves the necessary computational resource and real-time requirements as well as acceptable accuracy and robustness against dropped frames, occlusions and disappearance of objects.

The approach employs general assumptions about the cameras and visual discriminability of objects. The final implementation of the camera network [362] exploited the static camera assumption and built a detailed model of the background. The static background model enables us to implement a fast and reliable foreground object detector. To perform the association of foreground objects with the desired object to be tracked, colour histograms are compared using appropriate distance metrics. The method is illustrated in Figure 13.2. In a first step, foreground pixels in each camera are identified by comparing the camera image to the background image learned by each camera individually. Foreground constitutes moving objects that comprise objects of interest for tracking. These foreground pixels are then grouped into candidate objects based on their connectedness. In a second step, an association is performed between these candidate objects and a template database that contains the objects of interest (Figure 13.2(d)). To this end, a measure of similarity is employed according to [82] which is interpreted as the confidence of the validity of the association. This is depicted by different colours in Figure 13.2(c).

The association between templates and candidates is established by interpreting the problem of associating templates and candidates as a transportation problem, where the distances between the respective feature vectors are the transportation costs and the goal is to minimise all transportation costs. This problem can be solved optimally by employing the well-known Hungarian algorithm [227]. Additionally, the reciprocal of the transportation cost for a successful association is reported to other components as a confidence value of the current object. In each frame, the *object tracking* block searches for an assignment minimising the overall transportation cost of the system. In this way, a satisfying tracking performance is achieved even in difficult scenarios.

13.4.2 Object Handover

The *object handover* block coordinates the object tracking responsibility in the camera network. We apply a novel market-based handover approach [125]. A more detailed description of this approach is presented in Section 7.4. In this artificial market, the cameras act as traders and treat object tracking responsibilities as goods. For trading purposes, an artificial currency is used. This currency is provided by each object tracking responsibility as some utility over time. This makes these responsibilities worthwhile for cameras to own. The cameras can decide in a self-expressive manner on their own when to "sell" tracking responsibilities to other cameras using single sealed-bid auctions. Employing the Vickrey auction mechanism, which sells the good to the highest bidder for the second highest price, makes truthful bidding the dominant strategy among the participating cameras. Whenever a camera decides to sell an object, it initiates an auction for this particular object by transferring an

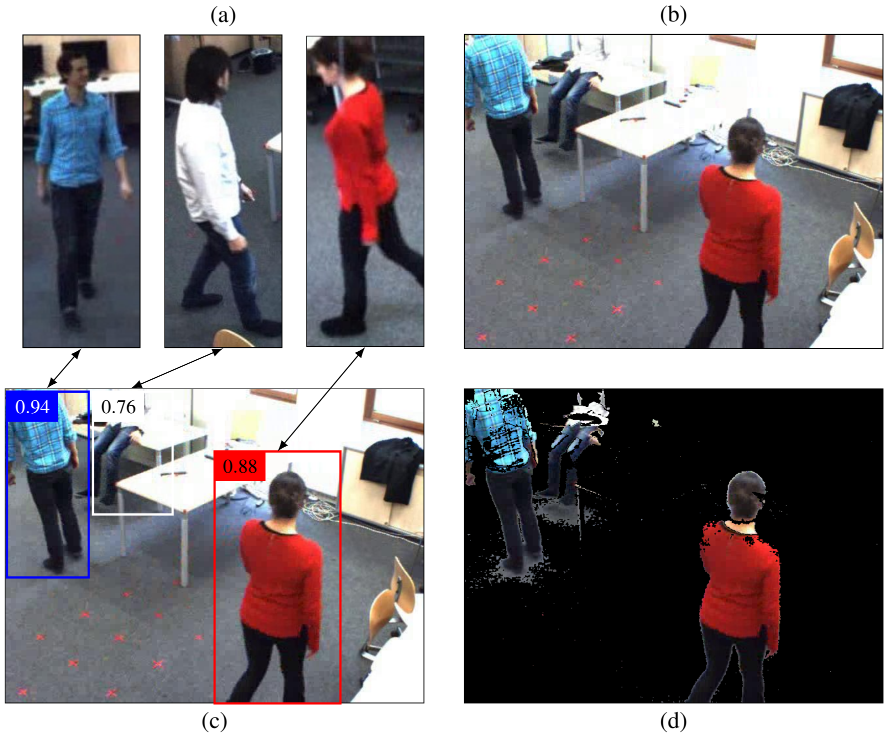


Fig. 13.2 Object tracking approach. (a) Template database images, (b) original image, (c) matching results between foreground objects and objects templates, (d) foreground image

object description to the other cameras. The receiving cameras request the state of the searched object from the *object tracking* block. This means, the *object tracking* block searches within its own FOV for the object and values the object based on detection confidence and visibility. The *object handover* blocks of the cameras return their valuation as a bid. The auctioneering camera selects the highest bidder and transfers the tracking responsibility. An important question for the selling camera is to whom to send the auction invitations. Without any a priori knowledge about the network topology, invitations could be broadcasted to all cameras. By following this policy the "best" camera for taking over the tracking responsibility will receive an invitation (and may respond with the highest bid). However, the BROADCAST policy causes a significant communication and computation load because each camera has to perform an object detection after receiving the invitation.

13.4.3 Topology Learning

If the auctioneering cameras are aware of the potentially "best" cameras in their neighbourhood, this knowledge can be exploited to significantly reduce the overhead. Such topological information can be initially assigned to the cameras or computed by means of multi-camera calibration during the deployment of the camera network. However, in a self-aware manner we learn the network topology by observing the bidding behaviour of cameras over time. Each camera keeps track of its local neighbours and uses artificial pheromones to express the likelihood of a handover to that camera. Whenever a handover has taken place, the artificial pheromone to the succeeding camera is strengthened. If no trading occurs, pheromones evaporate over time. This mechanism enables each camera to deal with network uncertainties and to adapt to changes in its neighbourhood topology caused by addition, removal or failure of cameras or changes in the movement pattern of the objects.

We exploit the learnt neighbourhood topology through three different communication policies for the handover: broadcast auctions to all cameras (BROADCAST), a smooth probabilistic multicast (SMOOTH) and a threshold-based probabilistic multicast (STEP) [125]. The SMOOTH policy sends auction invitations to all neighbours, with probability normalised to the current pheromone level. The STEP policy sends invitations to all neighbours with pheromone level above a certain threshold and to neighbours below the threshold with some (low) probability. Details and formal definitions to these different policies are also given in Section 7.4.1.1. Additionally, it is not only important to whom to advertise object tracking responsibilities, but also when to initiate such auctions. We distinguish between sending out invitations at regular intervals (ACTIVE) or only when the object is about to leave the FOV (PASSIVE). While a PASSIVE schedule ensures we keep track of each object continuously, in comparison the ACTIVE schedule achieves higher network-wide tracking utility as cameras assign tracking responsibilities to the camera "seeing" the object best at all times. Combining the variations in which cameras to invite and when to send out the invitations results in six different self-expressive handover strategies, each of which obviously influences tracking utility as well as communication and computational overhead.

13.4.4 Strategy Selection

While the six handover strategies allow us trade off communication overhead for tracking utility and hence influence the behaviour of the network, selecting a strategy is a difficult decision. The performance of each strategy strongly depends on factors such as the placement of the cameras, the movement patterns of the objects and the object tracking algorithm. In principle, we can follow three approaches for strategy selection: (i) a homogeneous assignment, where all cameras employ the same strategy from deployment time on, (ii) a heterogeneous assignment, where at least two cameras in the network use different strategies from deployment time on, and

(iii) a dynamic selection, where each camera can select its strategy autonomously during runtime.

As discussed in Section 7.4.1.3, we use online learning algorithms, specifically multi-armed bandit problem solvers, within each camera to learn the appropriate strategy for each node during runtime to trade off communication overhead for achieved tracking utility. The bandit solvers balance the exploitation behaviour, where a camera achieves high performance by using its currently best known strategy, with exploration, where the camera explores the effect of using other strategies to build up its knowledge [239, 238]. Dynamic strategy selection leads to a meta-self-aware behaviour of the individual camera nodes and by extension of the entire camera network. This allows the network as a whole to achieve a more Pareto efficient global performance than with any static strategy assignment at deployment time.

13.4.5 Resource Monitoring

Resource monitoring is an important aspect of computational self-awareness, and its main objective is to observe the available resources on the camera nodes. The monitored data is further used to build up models of resource consumption for each task a camera is capable of performing. The knowledge generated by the self-aware *resource monitoring* block is provided to the individual self-aware and self-expressive blocks on the camera. *Object handover* can use this information on the one hand to reason about submitting bids for a new object tracking responsibility and on the other hand to factor in available resources at the time of bidding for its valuation of the object. The *strategy selection* block uses the information from the resource monitor to reason not only about the performance of each task but also about its respective resource consumption. In our network, we currently monitor required processing power, available and allocated memory, and network traffic.

13.4.6 Constraints and Objectives

In order for a camera to become self-aware, it not only requires constraints, objectives and goals but also has to be aware of them. In our system every camera has its own constraints and objectives which it needs to consider for its self-aware and self-expressive operation. Constraints specify some limitations of the available resources (processing, memory and networking). These constraints help us decide on whether to bid for an object, but also help us evaluate the performance of the different strategies. In contrast to hardware-defined constraints, objectives are defined by the user during runtime or the designer of the system before deployment. Objects in our system drive the behaviour of the cameras and specify, for example, some quality of service parameters or certain tasks the cameras should achieve.

13.5 Camera Network Case Study

13.5.1 Camera Network Setup

For our experimental study, we set up a smart camera network in our laboratory at Alpen-Adria-Universität Klagenfurt. The network consists of six cameras, four of them in the laboratory room with overlapping fields of view and two more in the corridor and lounge area, respectively. An illustration of the camera layout is given in Fig. 13.3. Figure 13.4 shows snapshots of the six cameras' FOVs. This heterogeneous network is composed of different hardware platforms. Cameras 1 to 4 are equipped with Atom processors and connected via wired Ethernet. Cameras 5 and 6 are based on Pandaboards equipped with ARM processors and use WiFi for communication. All cameras run standard Linux and our distributed publish-subscribe middleware system to provide a flexible software platform for software development (cf. Chapter 11). The building blocks have been implemented in C++ and C# using the middleware services for communication and control.

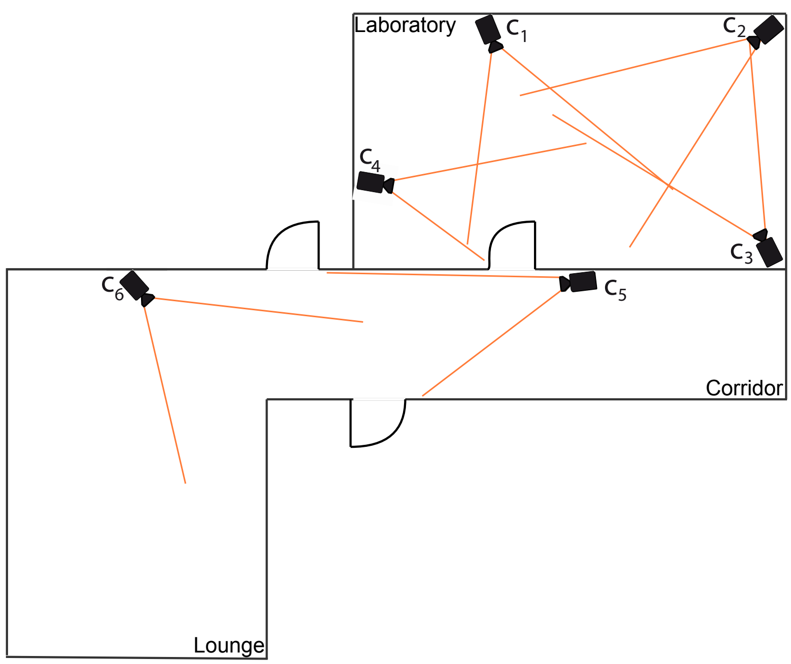
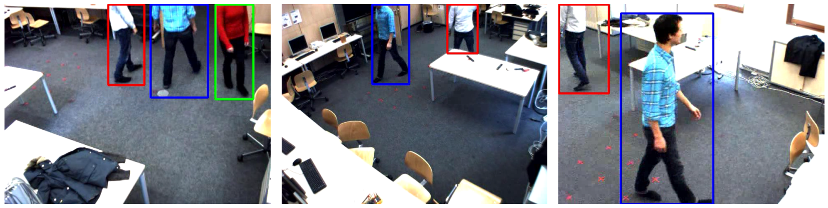
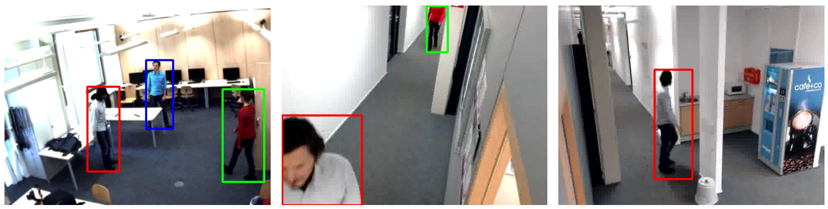


Fig. 13.3 The smart camera network composed of six cameras deployed in an indoor environment. The cameras are depicted by a black camera symbol and their FOVs are indicated by orange lines.



(a) Camera 1, frame nr. 2069 (b) Camera 2, frame nr. 688 (c) Camera 3, frame nr. 719



(d) Camera 4, frame nr. 1027 (e) Camera 5, frame nr. 2593 (f) Camera 6, frame nr. 1760

Fig. 13.4 Snapshots (a) to (f) of cameras 1–6 at different times. The images show the status of object tracking over time; the system tracks three people who are marked by red, blue and green bounding boxes, respectively.

13.5.2 Tracking Results

For the evaluation of our object tracking block we use the smart camera network with people walking through the indoor environment (as depicted in Fig. 13.4). The performance metrics used in the evaluation process are based on state-of-the-art metrics in the area of object tracking and multi-camera systems [31, 431, 422]. Detection of people and people tracking are evaluated per camera and across all cameras. Performance metrics such as sensitivity, precision and accuracy are used in the case of object detection evaluation. High-level metrics such as correct detected track (CDT), track detection failure (TDF) and false alarm track (FAT) show an overall view of performance of the tracking system.

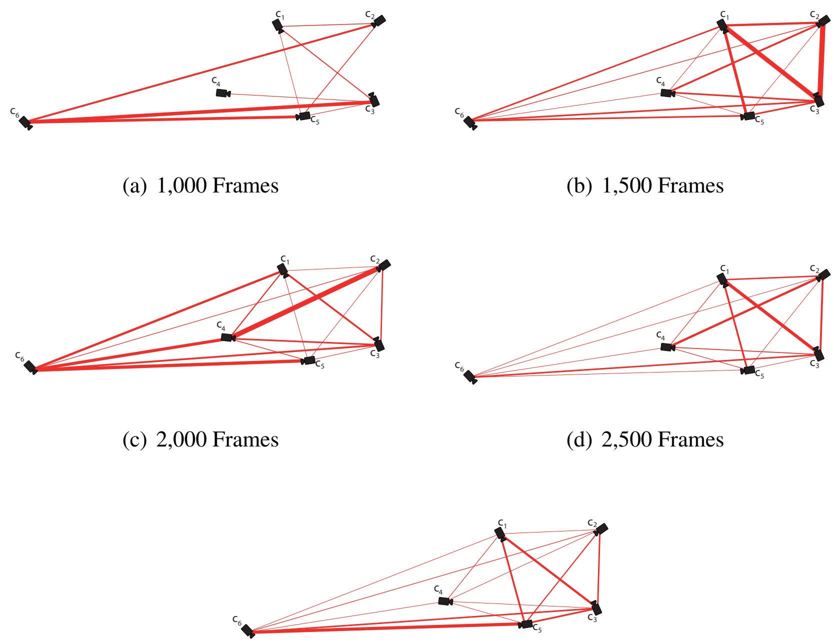
Tables 13.1 and 13.2 summarise the results of a typical scenario of concurrently tracking three selected persons independently walking around in the indoor environment for around 120 seconds. While the former shows for each camera the sensitivity and CDT for object detection and object tracking, respectively, the latter summarises the percentage of correct objects tracked between cameras. In this scenario, the tracked persons were not continuously visible to all cameras; at some points, participants were not seen by any camera at all. The cameras mounted in the laboratory (cameras 1–4) achieved better detection and tracking results compared to the performance of cameras 5 and 6. Here the tracking performance degraded slightly due to changes in lighting and object appearance.

Table 13.1 Performance of object detection and object tracking: single camera evaluation

Camera number	Object detection: Sensitivity	Object tracking: CDT
1	0.78	3
2	0.73	2
3	0.87	3
4	0.76	3
5	0.48	2
6	0.54	2

Table 13.2 Performance of correctly tracked objects between cameras

Camera pair	(1,2)	(1,3)	(1,4)	(1,5)	(2,3)	(2,4)	(2,5)	(3,4)	(3,6)	(4,5)	(5,6)
Percentage	66.67	100.00	100.00	66.67	66.67	66.67	33.33	100.00	66.67	66.67	66.67



(a) 1,000 Frames

(b) 1,500 Frames

(c) 2,000 Frames

(d) 2,500 Frames

(e) 3,000 Frames

Fig. 13.5 The graph shows the learnt topology at various times of the experiment exploiting the trading behaviour. The thickness of the red line indicates the pheromone level of the link.

13.5.3 Topology Learning

Our self-aware topology learning block builds up a neighbourhood relationship graph locally on each camera. Figure 13.5 shows snapshots of the graph for the entire network at various time steps in a typical test run. The thickness of the red lines indicates the strength of the artificial pheromone deposit on this link, and corresponds to the probability of an object transiting between the connected cameras. Initially, links are created between the camera in the lounge (camera 6) and those in the laboratory (cameras 1–4) due to misdetections of camera 5. Nevertheless, due to the evaporation of the artificial pheromones, these inaccurate links are "forgotten" over time. Furthermore, cameras can deal not only with errors induced by the tracking block but also with changes in the topology due to hardware errors, vandalism, or maintenance when cameras are being removed, added, or moved to a different location. Over time invalid links evaporate and a qualitatively correct neighbourhood graph emerges again.

13.5.4 Communication and Utility Trade-off

We evaluated the effect of the handover strategy on the overall tracking utility and communication overhead. Figure 13.6 depicts this trade-off between utility and communication for homogeneous strategy selection in our smart camera network. The utility is defined as the aggregated tracking utility of all cameras, and the communication is defined as the number of all sent auction messages during the entire tracking operation. Both utility and communication values are normalised by those from the best strategy (i.e., ACTIVE BROADCAST). The six strategies result in six different trade-offs for utility and communication. An operator overseeing the network can select a strategy based on the current situation and needs. These requirements may vary for example when the attention is directed from general surveillance to tracking a single person.

In addition, we also analysed homogeneous and heterogeneous strategy assignments, as well as dynamic strategy selection during runtime and their achieved trade-off in our CamSim simulation tool[1] [123]. Obviously, heterogeneous selection (black crosses) leads to many more outcomes in the objective space. The extension of the Pareto efficient frontier brought about by heterogeneity in comparison to the results by homogeneity is also apparent. However, it is also clear that the outcomes of many heterogeneous strategies are dominated, and many are strictly worse than the original outcomes from the homogeneous strategies. As an operator deploys networks in partially unknown environments and cannot foresee the dynamic behaviour of the objects, an optimal heterogeneous selection is impossible. This clearly benefits the self-expressive behaviour of our cameras, facilitating a dynamic strategy

[1] http://www.epics-project.eu/CamSim/

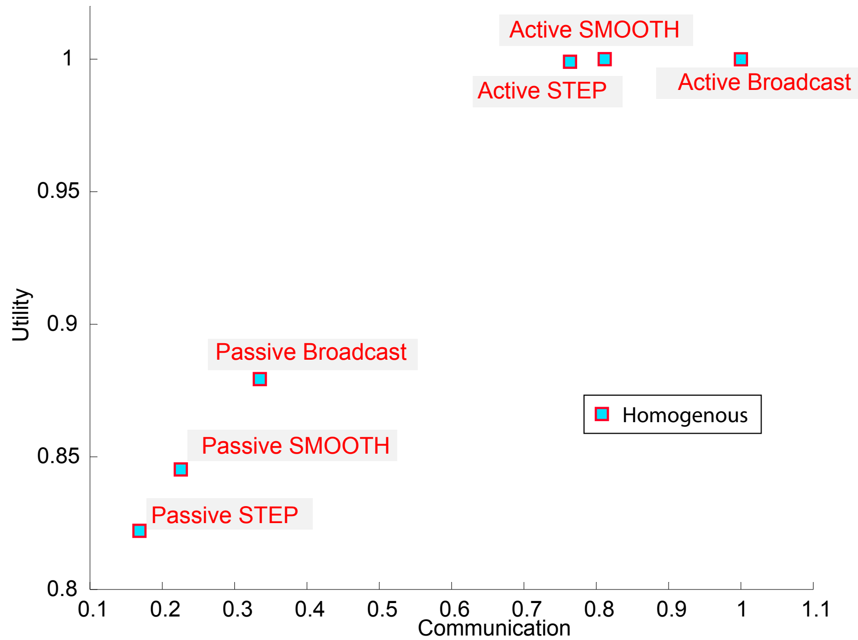


Fig. 13.6 Performance for two exemplary scenarios from our smart camera network showing homogeneous (red and blue squares), heterogeneous (black crosses), and dynamically learned strategy assignments (coloured symbols). The results have been normalised by the maximum value of the ACTIVE BROADCAST strategy and are averages over 30 runs with 1,000 time steps each [239, 238].

selection. Dynamic strategy selection (coloured symbols) is able to outperform the static (homogeneous and heterogeneous) strategies and to extend the Pareto front.

13.6 Conclusion and Outlook

This chapter presented how self-awareness and self-expression were implemented in a real smart camera network for a person tracking application. By enabling each camera to learn about its environment, its topology, and its performance, the entire network was able to perform continuously well to achieve a common goal. The facilitated building blocks allowed the camera network to face various challenges such as the limitation of available resources of the cameras, the continuous changes in a real scenario and the intrinsic problem of robustness in people tracking. These six different building blocks, encapsulating the entire processing, were embedded into resource-limited smart camera nodes and aggregated into a completely decentralised and thus scalable network.

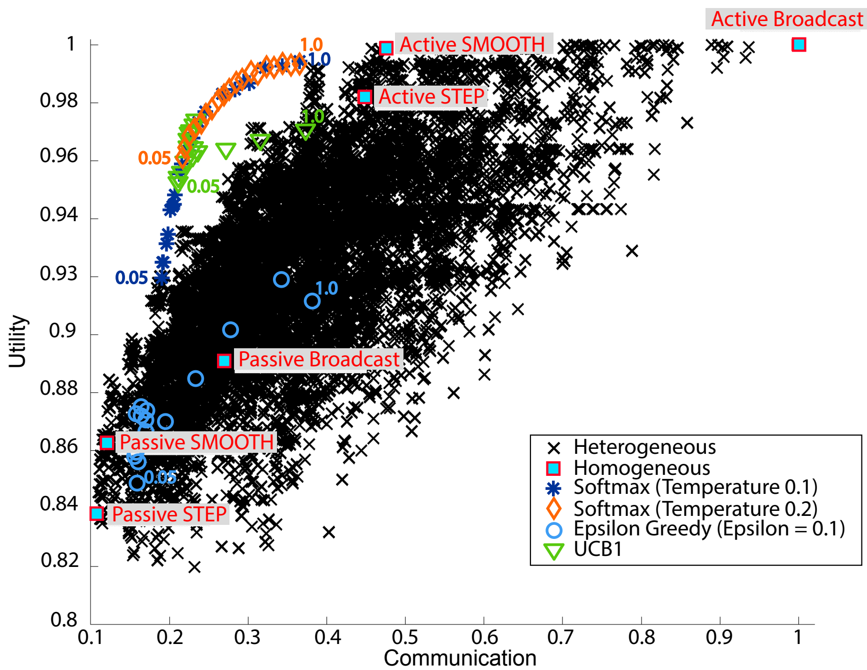


Fig. 13.7 Performance for two exemplary scenarios from our simulation environment showing homogeneous (red and blue squares), heterogeneous (black crosses), and dynamically learned strategy assignments (coloured symbols). The results have been normalised by the maximum value of the ACTIVE BROADCAST strategy and are averages over 30 runs with 1,000 time steps each [239, 238].

Nevertheless, the different blocks are implemented at different levels of self-awareness and self-expression. While the *object tracking* block is only *stimulus-aware*, other blocks such as the *object handover*, *topology learning*, or *strategy selection* are *interaction-aware*, *time-aware*, and *meta-self-aware*, respectively. Merging the different blocks in every single camera allows each camera, and by extension the entire network, to achieve higher levels of self-awareness and self-expression. However, one could still introduce additional blocks or refine existing ones in order to improve the overall performance. An example would be the *object handover* block which currently combines multiple strategies, each one consisting of an auction schedule and a communication policy. In the presented version, the auction schedules are static for all cameras, and communicate either at regular intervals or when the object is at a specified position within the FOV of the camera. In contrast, a camera could learn the best timing for a handover during runtime. In such a setting, the camera could start with an active approach and refine the timing based on the received bid in the advertised auctions.

The concepts of computational self-awareness and self-expression are not limited to camera networks alone. The previous chapter presented another application and the next chapter introduces a third one using real-time interaction between humans playing music. In fact, we are confident that self-awareness and self-expression could serve as an enabling technology for future systems and networks, meeting a multitude of requirements with respect to functionality, flexibility, performance, resource usage, costs, reliability and safety.

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