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Collective Awareness for Human-ICT Collaboration in Smart Cities

Nicola Bicocchi[1], Alket Cecaj[1], Damiano Fontana[1,2], Marco Mamei[1], Andrea Sassi[1], Franco Zambonelli[1,2]

1) Università di Modena e Reggio Emilia – Reggio Emilia – ITALY
2) EPOCA srl – Reggio Emilia – ITALY
{nicola.bicocchi, alket.cecaj, damiano.fontana, marco.mamei, andrea.sassi, franco.zambonelli}@unimore.it

***Abstract*— Future urban scenarios will be characterized by the close integration of ICT devices and humans. Citizens using their own capabilities integrated with ICT technologies could collaboratively constitute a large-scale socio-technical superorganism to support collective urban awareness and activities. This position paper, with the help of a representative case study in the area of intelligent transportation systems, identifies the key challenges for future urban superorganisms and proposes a two-tier architecture to support their development.**

***Keywords*— Cyber–Physical Convergence, Pervasive Computing, Self-Organization, Middleware.**

I. Introduction

The foreseen widespread adoption of sensor networks, actuators and computational resources capable of interacting with users' devices will transform our urban environments [3]. Citizens will have the possibility of being continuously connected in a situation-aware and socially-aware way, both with each other and with the objects/entities around, e.g., typically via some situation-aware social networking infrastructure [23].

This will eventually contribute to define a dense ecosystem whose individual components (i.e. citizens, devices, software services, sensors and actuators) will enable collaboration and adaptiveness between ICT devices and humans, towards the realization of advanced urban services. Such services can contribute towards the smart city vision along several dimensions from intelligent transportation systems, to environmental sustainability and participatory governance [17,11]. Such services will have impact on our way of living in the urban environments. Even more, they will change the very nature of our urban environments, turning them into *socio-technical urban superorganisms* [7, 23].

Future pervasive urban services, rather than being limited to sensing what happens in the city (as most current approaches do) will enable the complementary sensing, computing, and actuating capabilities of humans and ICT devices. The dynamics of such collaborative interactions will promote large-scale (i.e., collective) adaptive capabilities of perception, awareness, and action. That is, the overall urban environment will act as a single "superorganism" made up of many individual organisms (humans & ICT devices) and capable of directing its global behaviour towards the achievement of specific urban-level goals. However, engineering collaborative and coordinated services capable of harnessing human and ICT capabilities at a very large scale, challenges current engineering practices and middleware architectures. In this context, the contribution of this position paper is twofold:

- It sketches the key concepts of urban superorganisms and outlines the key research challenges to be faced to enable their deployment.
- It proposes a two-tier middleware architecture capable of tackling the identified challenges. A specific attention is put to the awareness module of the architecture.

The paper is organized as follows. Section II presents our global vision and also introduces a case study to ground the discussion. Section III discusses key research challenges. Section IV proposes a general-purpose architecture and details the awareness module. Section V concludes.

II. The vision of urban superorganism

People are increasingly equipped with smart phones with powerful capacities in terms of battery life, sensing, computational power and connectivity. At the same time, autonomous ICT infrastructures (sensor networks, security cameras, robots, etc.) are likely to pervade cities in the near future. Accordingly, the future urban environment is becoming a sort of very dense digital ecosystem.

A. Human vs. ICT devices

The "components" that are going to pervade urban environments are characterized by heterogeneous and complementary sensing, computing, and actuating capabilities, that can cooperate in a goal-directed way. In particular:

Sensing Capabilities

- *ICT Side.* The capabilities in sensing from the ICT side are provided by *(i)* mobile phones equipped with GPSs, accelerometers and cameras; *(ii)* sensors networks and smart objects that follow the Internet of Things paradigm;

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(iii) tags that exploit the near field communication technologies (NFC, RFID and Bluetooth).

- *Human Side.* From the human side, the five senses of humans, which in many situations can supply and be more accurate than ICT sensors, can be put at work for the community, due to the possibility of continuous access to social networks. In addition, users can make available via social networks any other information, thus acting as sorts of social sensors [15].

Computing Capabilities

- *ICT Side.* The capabilities in computing from the ICT side makes it possible to collect and digest very large amounts of urban data in a short time, and to perform some limited pattern analysis on such data.
- *Human Side.* From the human side, on the other hand, one can exploit the capability of recognizing complex situations and patterns (so called "human computation" [22]), which machines can hardly tackle.

Actuating Capabilities

- *ICT Side.* The capabilities in actuating from ICT side can be provided by *(i)* traffic controllers supporting pervasive solutions in the mobility dimension; *(ii)* public displays that will be exploited to promote adaptable and interactive citizens experiences; *(iii)* all kinds of actuators related to critical infrastructures (e.g., energy grid).
- *Human Side.* From the human side the key actuating element involved is the user himself, which can perform a variety of actions related to moving or moving items around or changing the properties of some physical entities. In other words, citizens could accomplish actions, by realizing an impact on the environment.

As a consequence, novel means of pervasive collaboration in the urban environment could be designed to exploit the complementary capabilities of individuals in an adaptive way.

The very large number of inter-connected individuals that can be found in urban environments, whether humans or ICT ones, can potentially be exploited to create what has been defined as a "superorganism" [7]. In particular, closing the sensing, computing, and actuating capabilities in a loop, and making such activities collaborative ones, it is possible to realize coherent collective behaviours, as it is observed in many natural situations, e.g., in ant colonies [2].

A single ant has very limited, local sensing and actuating capabilities, and little or no cognitive abilities. Yet, ants can indirectly coordinate their movements and activities, via spreading and sensing of pheromones in the environment, so as to exhibit, as a colony, very powerful capabilities of sensing (finding food in the environment), computing (finding the shortest path from food back to nest), and action (carrying large amounts of food in the nest). These capabilities make the whole colony seemingly intelligent and certainly adaptive in its foraging activities.

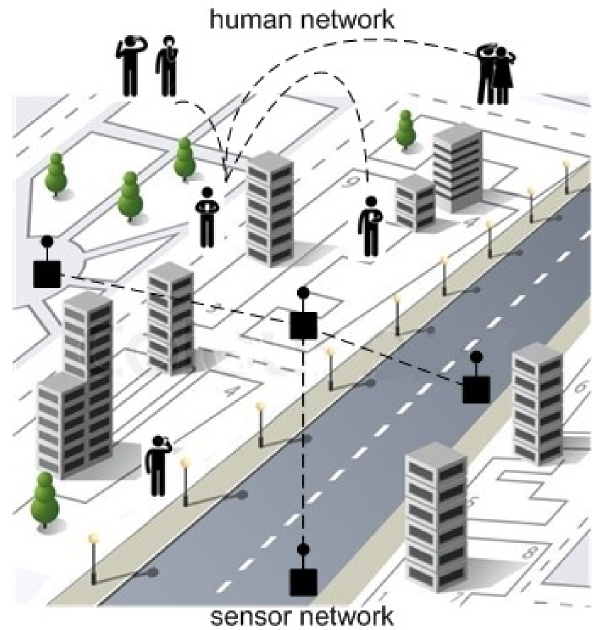

Fig. 1. Human-ICT systems coordinate their behavior in a smart city scenario. Humans and ICT devices can interact both via a ad-hoc networking and via cloud services. Applications can rely on sensing, computational and actuating capabilities of both kind of actors.

Future collectives of socio-technical entities (i.e., citizens and ICT devices) will be most likely continuously – and possibly invisibly – involved in distributed and participatory sensing campaigns. The results of such *collective sensing* activities will then promote a sort of participatory perception that can enable *collective awareness* (by computing, by thinking, and by communicating) of urban facts and issues, and urban dynamics. Based on such shared understanding, it will be possible to plan for specific *collective actions* aimed at fixing problems or adaptively steering urban dynamics.

Previous works in opportunistic and participatory sensing have tried to involve users by making use of their devices as sensors [10, 14]. On the opposite side, other works try to detect events or situations by observing users activities on online social networks [16]. However, these works lack of a general and unified vision and do not completely deal with the complexity of the global scenario, i.e. they don't explore all the possible convergences of humans and ICT devices. Moreover, they do not fully make use of the very large number of inter-connected individuals and their complementary capabilities to realize a collective awareness.

Recent research efforts in the field of self-adaptive and self-organizing systems have focused on defining a catalogue of bio-inspired mechanisms [12], with the intent to overcome the limit of ad-hoc implementations that prevent their systemically reuse. Thus, the basic idea is that of providing the *bio-inspired self-organizing pattern modules* with a set of reusable patterns that could be used to ease engineering of artificial and collective behaviors of urban superorganisms. It is probable that the complementary capabilities of humans and ICT devices and the ability to coordinate and organize them could overcome current approaches and promote collective awareness and complex behaviors. In line with [12], we think that bio-inspired algorithms could be helpful to achieve complex and coordinated behaviors.

On the basis of such patterns, it will be possible for the socio-technical collective of humans and devices to put in place a variety of collaborative collective behaviours, expressing various forms of "urban awareness and intelligence", and promising to dramatically change the way we move, live, and work, in our urban environments.

B. Case study scenario

In order to ground the discussion and exemplify the above concepts, let us now introduce a case study scenario related to the governance dimension in smart cities. In particular, we focus on a city-wide Intelligent Transportation System (ITS): an infrastructure aimed at relieving congestions, improving safety, enhancing productivity [21]. The achievement of these three main goals can be realized in terms of the superorganism's perspective.

Following the superorganism's paradigm, citizens can cooperate with each other to steer the behaviour of the city (in terms of mobility dynamics), by interacting with its transport infrastructure and by sensing the environment (see Fig. 2).

Collective Sensing

Both humans and ICT devices concur in sensing activities for the ITS. In addition, humans can exploit their personal mobile devices to share any traffic-related event they are dealing with, or any mobility activity they are doing, and ICT devices can, for example, autonomously monitor in real-time the amount of vehicles at main intersections. Sensed data plays a key role in the effectiveness and efficiency of the ITS to provide real time data feed on what is happening in the city.

Collective Awareness

Real-time data streams provided by people and sensors deployed in the city can be processed by some *specification-based* and/or *learning-based* techniques [9] owned by a context inference platform (such as the two-tier middleware architecture proposed in Section 4), in order to compute the actual situations faced by people on the move and ICT devices installed on the transport infrastructure. Thus, for example, the situation that occurs during traffic congestions can be inferred by gathering together the road characteristics context, the vehicle velocity and model contexts, and the weather context [20]. On the basis of these assumptions, the ITS could be endowed with situation-aware modules that aim to *(i)* analyse specific recurrences and *(ii)* infer the traffic network flow forecasting [6].

Collective Actions

The ITS manager could model current traffic conditions dynamically and take steering decisions accordingly, in order to optimize traffic flow by enhancing efficiency (e.g., by recommending re-routings, intermodal routes and viability changes) and safety (e.g., by inferring accident-like situations before they occur, and acting to avoid them). Therefore, the ITS manager can suggest corrective actions directly to the citizens, to the infrastructure and to the urban planning authority of the city, accordingly to the fulfilment of the ITS's intents introduced above.

III. Challenges for Superorganism Architectures

We identified many challenges towards the realization of an infrastructure to support novel urban superorganisms features, i.e., to support innovative services needing collective coordination, awareness and adaptation.

A. Support for heterogeneity and interoperability

Whether they are humans equipped with a mobile phone or autonomous ICT devices, the software architecture has to be able to realize an abstraction layer in order to achieve the same goal on different individuals, by adapting and exploiting their heterogeneous and complementary sensing, actuating and computing capabilities.

The complementary use of sensing and *understanding* capabilities of humans and ICT devices has to lead the coordinated learning process towards reconstructing a collective awareness of the state of the city. A common example that fits this situation is expressed by the capturing of pictures of a traffic jam both from users cameras and *Closed Circuit TeleVision* (CCTV) cameras, to make sure that all the images are properly tagged with information automatically generated by devices (e.g., amount of vehicles involved) and further enriched by humans (e.g., the reason they are stuck in traffic), due to their higher classification capabilities.

The challenge is to realize an abstraction layer able to continuously observe the superorganism status and plan strategies to reach specific goals by making use of heterogeneous individuals with evolving sensing, actuating and computing capabilities.

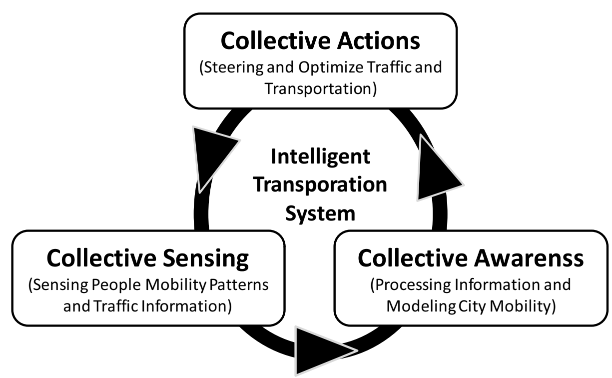

Fig. 2. Collaborative sensing, awareness and action among humans and ICT systems can be put at work to realize intelligent transportation systems.

B. Support for dynamic re-configurability

As emerged by the heterogeneity challenge, the software architecture should show a certain degree of flexibility. Thus, the ability to dynamically execute heterogeneous code with heterogeneous sensing, actuating and computing capabilities is a key challenge to be tackled. For instance, in the case of an accident report executed by a citizen, the architecture has to support a service that requires the user interaction and thus has a user interface; while, in the case of the same task executed by a remote camera, the latter has to support services exploiting the sensing, actuating and computing capabilities of devices.

Furthermore, dynamic service composition and re-configuration is needed. The design of an architecture dealing with these challenges will make applications interoperable and able to self-reconfigure and self-optimize depending on the execution context.

C. High degree of awareness

A prerequisite in this challenging scenario is a high degree of awareness. In this direction, as technologies evolve and improve, also new types of sensors become available and affordable from a cost perspective. Chemical, electric, optical, proximity and position sensors can provide data about environment, weather, presence or movements of and between different entities part of the city life. Furthermore humans can also act as a type of social sensor through social networks or their mobile phones signal [4,13].

This set of sensors, in fact data sources, will produce, continuous streams that will generate a very big data set, specially, if we consider the temporal dimension of data. From a computation concern, the issue is about finding the suitable kind of algorithms and from this perspective, machine learning algorithms are useful for dealing with big datasets. These types of algorithms will integrate the awareness module, and can also be used to elaborate images and for example detect vehicles or recognize faces

More specifically, one of the most significant issues pointed out by Zhang et al. [24] concerns the heterogeneous learning: comparison and fusion of data provided by multiple sensors is a challenging task that can be addressed to machine learning practices.

The high-level awareness acquired by the individuals through sensors should be used to infer complex situations and create a sort of collective awareness of the surrounding physical and social environment. The challenge here is to realize a software infrastructure that is able to:

- Opportunistically sense and recognize many heterogeneous kind of situations.
- Self-reconfigure the awareness subsystem itself. The reconfiguration should be based on the partial awareness acquired by the infrastructure and is aimed to *(i)* improve the recognition accuracy by optimizing the classification modules and to *(ii)* preserve computational resources.
- Exploit the awareness of other individuals of the superorganism to infer complex situations and behavior in the urban environment that involve groups of individuals.

All these challenges have to be solved to support for instance, scenarios where the individuals sensing capabilities have to be exploited to acquire environmental information.

D. High degree of interconnection

As emerged by the case study, individuals have to be connected and able to exchange messages for both *(i)* supporting collective behaviors (e.g. the coordination effort required to steer individuals to take photos of a road intersection), and *(ii)* gathering individual awareness to infer complex situations that involve the superorganism rather than specific individuals. It is worth noticing how this requirement calls for innovative data fusion techniques. In fact, at both the individual and superorganism levels multiple data streams of information sources have to be processed and put together to build up a coherent picture of operating conditions.

E. Strategies for dynamic selection

One should evaluate which individuals are more suitable to be involved by taking in account different constraints. For instance, in the case study, many CCTV cameras and humans could be available at the same time to capture traffic information to feed the ITS. Strategies taking into account different constraints (e.g. geographical areas, individuals status and sensing, actuating and computing capabilities) are needed to pick up the most affine individuals for the desired behavior. These strategies could be based both on explicit interactions (e.g., sending a message to an individual) or implicit interactions (e.g., subsampling the whole population of individuals satisfying specific constraints).

F. Mixing bottom-up and top-down design approaches

Designing with a top-down approach means that all the requirements of a software architecture have to be taken in account a priori; systems engineered in this way have a predictable and measurable behavior but are not capable of coping with dynamic execution-context; while systems designed with a bottom-up approach are more robust and suitable for a pervasive environment but predicting their behavior and controlling them "by design" is not an easy task. In the design of architectures for urban superorganisms, both of the two approaches are needed and finding and tuning the optimal trade-off between them is a key challenge to be tackled [3,19]. A first case identified by the case study is that of the coordination between individuals and their respective activities and mobility patterns.

We claim that the resulting superorganism should rely on self-organization in order to take advantage of collective behaviors, by taking inspiration from natural metaphors. However, we claim also that emergent behaviors have to be controllable "by design" and thus understanding the trade-off of the two approaches and to what extent they can co-exist is a key challenge to be tackled to design controllable collective behaviors.

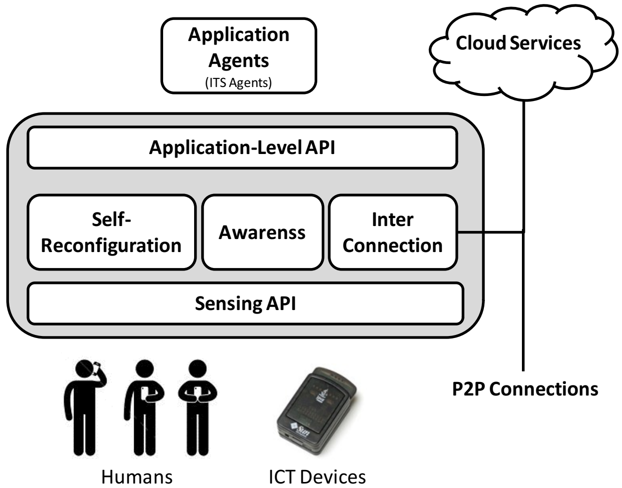

Fig. 3. Architecture for individuals in the superorganism. The architecture provides a *Sensing API* enabling access to the SAC functionalities (sensors, actuators and computational capabilities) provided by individuals, and an *Application-level API* allowing applications to interact with the middleware. Moreover, the middleware provides components supporting Self-reconfiguration, Awareness and Interconnection. The latter components supports both connection with cloud-components and with other middleware infrastructures in a P2P way.

IV. An Architectural Proposal

By taking in account the challenges emerged in the previous section, we propose a two-tier middleware architecture. The former, deployed on individuals, is able to support the resulting superorganism; the latter hosts the centralized control engines, which are able to actuate urban superorganisms through the dynamic injection of pervasive services.

A. Overview

Our primary goal is to develop a middleware, on top of individuals, enabling urban superorganism features. According to the challenges described in the previous section, the middleware is characterized by a layered architecture, as depicted in Fig. 3. The first layer is an abstraction layer that exposes APIs to access to the SAC functionalities (sensors, actuators and computational capabilities) provided by individuals. To deal with their heterogeneity, it exposes only the APIs supported by the current individual.

On top of this layer our middleware provides support to:

- **Self-reconfiguration.** To enable injected services to self-reconfigure and adapt to the current execution context. It is up to the self-optimizing and reconfiguring module to enable applications to self-reconfigure and thus deal with the re-configurability challenge, given applications specific strategies. In order to realize a reconfigurable application, the software model that best fulfills this requirement is the service-oriented architecture.
- **Interconnection.** To enable distributed operation the interconnections module enables connecting both with cloud services and with other devices in a peer-to-peer decentralized mode
- **Awareness.** Awareness is supported by the awareness module. It has been designed to provide both: *(i)* individual awareness (up-to-date information about individuals' context) [1]; and *(ii)* collective-awareness (up-to-date information about the superorganism's context).

The role of the Application-level API is to support the execution of novel pervasive services that are dynamically bound with the middleware. This feature could be implemented through a container-based approach [5], which supports dynamic execution by providing a common environment with a set of reusable functionalities.

It is finally worth noticing that the proposed infrastructure is also important to support privacy of data. In fact, the risk of matching a signal coming from a personal device and a name record in a database increases with the accumulation of data. Therefore the more can be done and kept within the personal handset, the greater the preservation of privacy [18].

Information connected by the individuals can be aggregated both on cloud servers, and in a decentralized way to obtain a global view on the city dynamics (see Fig. 2). This would allow the creating of global application involving multiple users, devices and services (i.e., the super-organism).

B. Awareness Layer

As shown in Fig. 4, the awareness layer uses three conceptual layers to reach its goal, the sensor, the classifier and the awareness layer. Internally, components of the sensor layer filter sensorial data stream coming from heterogeneous sensors; while components of the classifier layer classify them using general or specific purpose algorithms; finally, components of the awareness layer fuse classification labels to obtain a coherent overall picture of the situation.
The awareness layer, in particular, by enabling a control layer, interacts with the sensor layer and with the classifier one, in a feedback loop. That means, the sensor layer can use the data computed by the awareness layer to actuate decisions/intents (e.g., to favor and obtain desired user behavior and/or participation). In this direction, collaborative filtering techniques could be used, to recommend possible optimal solutions or alternatives, to entities of the superorganism.

In a similar way the control layer, using data from the awareness layer, gives feedback to the classifier layer. Describing in further detail the classifier layer, some of the algorithms that could be used to analyze and gain insight to the data are clustering techniques which group the data by degree of similarity and map them into spatiotemporal plots. [8].

The awareness layer itself could use other machine learning techniques, such as decision trees and neural networks, to recognize patterns and thus infer information about the properties of those data. As machine learning algorithms have their limits, other intelligent ways of accomplishing some of the tasks are human computation and crowd sourcing, which have to be supported/implemented by the first layer of the architecture.

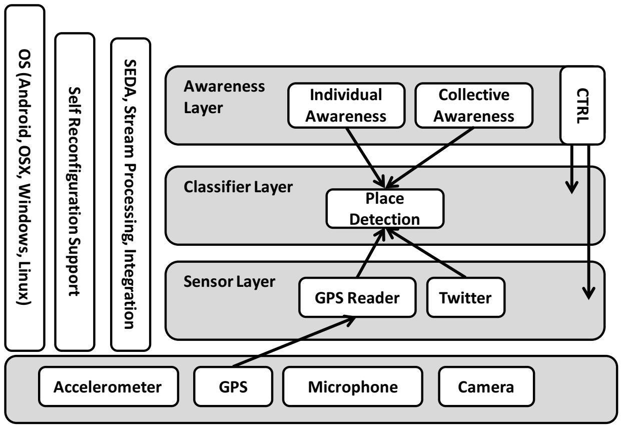

Fig. 4. Awareness module internals. This module is based on a hierarchy of components processing low-level sensor readings, classifying them, and fusing information into high-level context-description. A Control component enable the dynamic reconfiguration of the modules so as to improve performance by (de)activating components dynamically.

Inspired by biologic mechanisms, we designed the awareness module to be able to autonomously self-reconfigure. Particularly, by making use of its high level information, it is able to dynamically enable and disable specific data streams (and, thus, their corresponding sensors) and classification components for *(i)* improving the recognition accuracy by optimizing the classification modules, for (ii) adapting to evolving situations and for *(iii)* saving resources.

V. Conclusions and Future works

As we have discussed in this paper, we believe that it will be possible to exploit socio-technical superorganisms to deliver complex collective urban-level services. In our opinion, innovative collaborative collective behaviours expressing various forms of "urban awareness and intelligence" will take place, and dramatically change the way we move, live, and work, in our urban environments. However, to reach this goal, many research challenges need to be addressed, and suitable middleware infrastructures have to be developed. At the time of writing, we are in the process of completing a first prototype implementation of the proposed architecture. In addition, our future work includes testing the infrastructure in controlled (campus-level) environment and, later on, start experiencing it on-the-wild with simple urban awareness services.

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