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Integrating social sensors and pervasive services: approaches and perspectives

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Abstract

Purpose – The key purpose of this paper is to overview the many issues related to the integration of social sensing and pervasive sensing in the support of adaptive context-aware services.

Design/methodology/approach – From the analysis of existing proposals and prototypes, the authors found out that the process of integrating social and pervasive sensing can follow a limited number of approaches, which enables the authors to properly frame the proposals existing in the literature (and/or available as prototype infrastructures) according to a simple taxonomy, which is very useful to make the survey much more effective than a simple list of systems and proposals.

Findings – The taxonomy shows that, when integrating social sensing with pervasive sensing, it is possible, at one extreme, to exploit social network as a mere source of information and have such information flow towards the infrastructure supporting the execution of pervasive computing services. At the other extreme, it is possible exploiting a social network as an infrastructure for the integration, by having data from pervasive devices flow towards social networks. In between the extremes, different means can consider to have social networks and pervasive infrastructures converge towards each other to enable the integration of social and pervasive sensing.

Originality/value – Besides introducing the main concepts related to social sensing and framing the key approaches that can be undertaken to pursue the integration with traditional pervasive sensing, the authors go further discussing open issues and key research challenges behind their seamless integration.

Keywords Social networks, Context-awareness, Pervasive services, Social and pervasive sensors

Paper type Research paper

1. Introduction

Every day social networking services (i.e. Facebook, Twitter, MySpace, LinkedIn, Orkut, etc.) attract millions of users and absorb from them detailed contextual information about their individual interests, preferences, social relations, and activities. Accordingly, social networks have the potential to act as powerful "social sensors", i.e. as sorts of sensing devices capable of perceiving and reporting massive amounts of information about fact and events occurring both in the real and social worlds.

Indeed, many successful ways of exploiting social networks as sort of social sensors, so as to mine a variety of social facts, already exist (Sitaram and Huberman, 2010). However, in this paper we are specifically interesting in the exploitation of social sensors in the context of pervasive (aka ubiquitous) computing services (Weiser, 1991; Satyanarayanan, 2001; Saha and Mukherjee, 2003). Pervasive computing services already intensively exploit ubiquitous ICT sensing devices (i.e. "pervasive sensors")

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to support context-awareness and adaptability to context. Just think at mobile phone applications exploiting compasses and built-in accelerometers to provide augmented reality services. Here we argue that more sophisticated levels of context-awareness could be provided by integrating within pervasive services the capability of social sensors other than that of pervasive sensors (Figure 1).

Social sensing capabilities well complement traditional means of pervasive sensing, in that there are fact and events that could be effectively sensed by social sensors but not by pervasive ICT sensing, and viceversa. Thus, integrating social and pervasive sensing makes it possible to account for both the physical and social context, and makes it possible to deliver services that exhibit higher-degrees of adaptability and personalization (Bonchi *et al.*, 2011; Beach *et al.*, 2010).

The key objective of this paper – which we think can be of help both to scientists and practitioners to get acknowledged to such a fascinating emergent area – is to overview the many issues related to the integration of social sensing and pervasive sensing. This includes positioning the problem in the context of the broader area of social mining (Olgun and Pentland, 2008; Eagle *et al.*, 2009), motivating the need for such social-pervasive integration, and surveying the key proposals in the area.

Interestingly, from the analysis of existing proposals and prototypes, we found out that the process of integrating social and pervasive sensing can follow a limited number of approaches, which enables us to properly frame the proposals existing in the literature (and/or available as prototype infrastructures) according to a simple taxonomy, which is very useful to make our survey much more effective than a simple list of systems and proposals. Such taxonomy shows that, when integrating social sensing with pervasive sensing it is possible, at one extreme, to exploit social network as a mere source of information, and have such information flow towards the infrastructure supporting the execution of pervasive computing services. At the other extreme, it is possible exploiting a social network as an infrastructure for the integration, by having data from pervasive

Figure 1.
Coupling social sensing and pervasive computing

devices flow towards social networks. In between the extremes, different means can consider to have social networks and pervasive infrastructures converge towards each other to enable the integration of social and pervasive sensing.

The many representative proposals and applications from the literature that – according to the above taxonomy – have been analyzed and are surveyed in this article, each has specific peculiar and interesting characteristics. However, beside this, a number of challenging research issues is still open, which we (as an additional contribution of this article) analyze and discuss.

The remainder of this paper is organized as follows: Section 2 provides a general overview on social sensing and its applications, and motivates the need for integrating social sensing in pervasive services. Section 3 frames the possible approaches to such integration, and surveys accordingly a number of relevant proposals in the area. Section 4 deepens on prevalent research challenges and open issues beyond integration. Section 5 concludes the paper.

2. Social sensors in the pervasive scenario

The pervasive (ubiquitous) computing scenario generally considers an environment densely enriched by portable and mobile devices like modern smart phones, tablets, and notebooks. Such kind of pervasive devices, being enabled with sensorial capability (i.e. GPS, bluetooth, gyroscope, microphone, camera, etc.) are exploited for the provisioning of context-aware, adaptable, and personalized services that closely interact with the surrounding world. The process of exploiting such sensors to infer data about activities of people is called social sensing in Olgun and Pentland (2008), Eagle *et al.* (2009), while in Miluzzo *et al.* (2008) authors use the term people-centric sensing for the same meaning.

We expand on this definition of social sensor, considering any source of information that can be identified in modern social networking and web tools that expresses some situation or fact about users (i.e. their preferences or scheduled activities) beside individual interests, preferences and activities in the social sphere. In this vision a social network becomes similar to a sensor providing information about people and the environment. Such kind of sensors can contain information about what the user is doing (i.e. Twitter), where he/she is (Foursquares) and also other contextual information (by a Facebook status updates or pictures posted on Flickr (Sakaki *et al.*, 2010)). However, even what a user searches for on Google or what it buys online can be implicitly considered as a sort of social sensor, if used for that purpose.

It is beyond any doubt that the capabilities of social sensing can further enrich the pervasive scenario, by complementing the available information and thus enabling higher levels of context-awareness.

2.1 Social sensors vs pervasive sensors

Given the above definition, we distinguish social sensors from pervasive sensors, as we intend the latter as sources of information by ICT physical devices. Of course we are aware that pervasive sensors sometimes act as social sensors too, i.e. they can be used to detect the same kinds of social facts that social networking tools capture. For instance, a friendship between two people can be detected either from proximity sensor data or by mining their Facebook network. In any case, the potential of social sensors can go much beyond that of pervasive sensors, since:

- There are facts that exist only in users' mind (i.e. an user likes a particular movie) and cannot be sensed by other pervasive sensing means, but only in the case that such states of mind are reflected in their interactions with social networking sites.
- There are facts revealed by social sensors and could be potentially revealed also by pervasive sensing, but simply happen to occur in their absence (i.e. a user posting a geo-tagged picture on Flickr can reveal locations even in absence of localization sensors).
- There are facts that can be recognized only by coupling social and pervasive sensors (i.e. Paul and other people are localized by their GPS-featured mobiles in the same restaurant, since a bunch of them belongs to the same classmate dedicated Facebook group, Paul is having dinner with his schoolmates).
- Social sensors express information about future situations (i.e. reading a shared calendar or the Facebook status of a user) that would otherwise hard (i.e. via inference on historical data) or simply impossible to obtain.
- The collaborative feature (Lukowicz *et al.*, 2012) beyond social networks leverages social sensors understanding from micro local facts to macro emerging phenomena, thus moving towards the recognition and comprehension of complex social situations (i.e. people posting their complaints about daily life on a social network as growing in prices, people loosing their job, etc could explicate the economic circumstances, as an economic recession, taking place in the country).

Since social sensors, as said before, could act as traditional pervasive sensors and can be used to detect the same kinds of facts, share the same issues of accuracy and timeliness as other sensors. Sometimes indeed perhaps more so, since, for example, sensing using Facebook or a diary requires that the user keeps her Facebook/diary page up to date in the normal course of events, which many people do not do, or do only inconsistently.

2.2 Current (non pervasive) social sensing apps

Beside their application to pervasive computing scenarios, social sensors have been recognized as a powerful tool to detect and predict collective patterns of behavior (Sitaram and Huberman, 2010; Fujisaka *et al.*, 2010), possibly associated with events occurring in the real world (Mendoza *et al.*, 2010; Van den Broeck *et al.*, 2010). Indeed, several experimental and commercial systems exist, where users' social information parsed from the web is used to support commercial, demographic, and emergency management activities.

Such systems typically share a twofold approach to social sensing. In some of them, social sensing emerges a side effect of people using service designed for other purposes. In this case social information is implicitly derived from digging on user expressed preferences, profiles, on content of the query been performed on a search engine, etc. Oppositely, the social sensing purpose is made explicit when people consciously approach a web service recording people-generated content to be shared between members of a community, as modern social networks do.

As far as implicit social sensing is concerned, e-business sites (like Amazon (Ziegler *et al.*, 2008)) analyze the purchasing behavior of their costumers in order to recommend additional products that may be of interest. Likewise, Google Trends[1], by using Google searches as a sensor, can be very effective in measuring social and commercial trends (Choi and Varian, 2009).

As far as social networking tools and explicit social sensing is concerned, current research focuses on the most popular tools such as Flickr, Twitter, and Facebook, due to the critical mass of information that can be extracted from them.

In Crandall *et al.* (2009), the authors present techniques to automatically identify the location of points of high interest all over the world, by analyzing the spatial distribution of millions of geo-tagged pictures posted on Flickr. Results accord with common sense opinions and travel guide suggestions.

In Sakaki *et al.* (2010), it is demonstrated that Twitter, thanks to its real-time nature, can effectively act as a seismometer for the detection of earthquakes, simply by observing user tweets. More generally, the ability to identifying global trends and events via Twitter is the core of numerous applications, such as Tweettronics[2], oriented to identify market trends and brand awareness for marketing purposes.

Facebook is often cited for studies on network evolution and peer (as nodes of a graph) behavior. Of the many examples in literature (Von Arb *et al.*, 2008; Grob *et al.*, 2009) of services extracting social features from a network, we mention (Hui-Yi and Hung-Yuan, 2010), which studies and analyses the patterns of friend-making, and the work of Viswanath *et al.* (2009), which studies the dynamic properties of the friendship network. Both of these works have the potential for improving our understanding of the dynamics of real-world social networks (and therefore have potentially high commercial and social impact).

2.3 Towards pervasive social sensing apps

The above examples of social sensing applications focus on large-scale statistical collective behaviors, and are not specifically aimed at exploiting the knowledge extracted for the sake of improving pervasive services (or deploying innovative ones). Nevertheless, there are many signals that the trend towards the integration of the social networking and the pervasive computing world is imminent.

Apple and Google are both already experimenting context aware services based on GPS coordinates and small communities of friends. Such applications, as Apple FindMyFriends or Google Latitude[3], store and process mobile data from users moving in the cities and provide them real-time services for meeting friends together, share their positions or plans for activities. Analogously, Foursquare is a location-based social networking web site for mobile devices based on users GPS positions and geographical commercial point of interests (i.e. restaurants, pubs, shops) where users "checking-in" at venues award user points and/or discounts on available services. Both Facebook and Twitter now integrate the possibility of automatically geo-locating users and posts, which is a form of integration between pervasive sensors (i.e. GPS) and social ones (the posts themselves).

Other emerging social networking tools (known as participatory sensing) have been explicitly conceived to facilitate collecting sensorial information for pervasive usage. For instance, in the area of traffic detection, Traffic AUS[4] and Waze[5] propose social networks for car drivers, in which the data produced by drivers about the traffic situation can be exploited by other drivers for real-time navigation. Again, Green GPS (Ganti *et al.*, 2010) is a navigation service that uses participatory sensing data to map fuel consumption on city streets, allowing drivers to find the most fuel efficient routes for their vehicles between arbitrary end-points.

Although the road towards the extensive and systematic integration of pervasive services and sensors with social sensors is long, a great deal of research exists in this direction, showing that such integration can occur in many diverse ways.

3. Classification and survey of approaches

We have studied and analyzed a large body of recent proposals related to the integration of social and pervasive sensing, specifically aimed at improving and/or facilitating the development of pervasive services. In these works integration is mainly realized by one between social network and pervasive service to act as an infrastructure for integration, and the other to serve as a mere source of information. In between the two extremes, social networks and pervasive infrastructures could converge towards each other to enable the integration of social and pervasive sensing at different levels.

On this basis, we have identified and framed four key ways in which such integration can be architected and pursued (Figure 2).

First, at one extreme, one can exploit social networks as mere sources of information, to extract social information from them and have such information flow towards the infrastructure supporting the execution of pervasive services (arrow A in Figure 2). That is, social networks feed pervasive services and applications by bringing social sensing data at the same level of pervasive sensing. This way of approaching the integration is the one that more directly reflects our own research efforts (Mamei *et al.*, 2010; Ferrari *et al.*, 2011; Ferrari and Mamei, 2011). Related proposals are analyzed in Section 3.1.

Second, and somewhat reversing the previous view, one can exploit social networking infrastructures (the place in which social sensing resides) as a way to collect and organize the data coming from pervasive sensors (arrow B in Figure 2). In this way, pervasive sensors are brought up to the same level of social sensors, and there integrated with them. Possibly even more important, in this way of approaching the integration, the social network infrastructure is elevated to the role of middleware for pervasive services and applications, i.e. as a socio-pervasive medium to distribute and fetch pervasive content and information. Proposals in this direction are analyzed in Section 3.2.

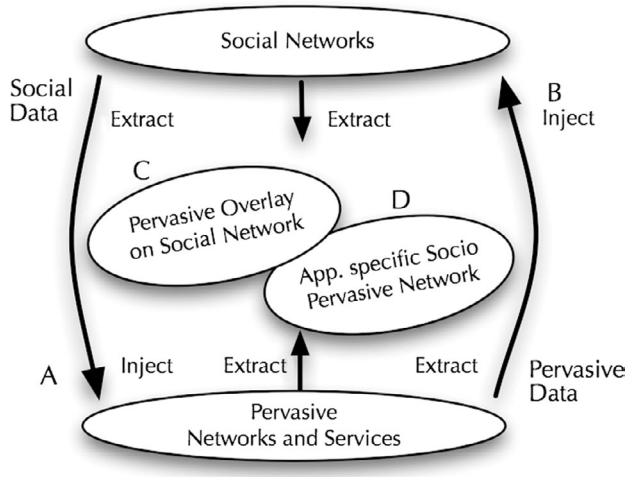

Figure 2. Approaches to integrate social sensing and pervasive services

Third, and alternatively to the second view, one could think of exploiting existing social network infrastructures not "as they are", but rather as the ground upon which to build an overlay in which to perform the integration (oval C in Figure 2), by extracting information from both pervasive services and social sensors and bridging them in a social network overlay. In this way, the existing functionalities (i.e. for information diffusion and distribution or for event notification) of the social network infrastructure can be properly extended to account for the specific needs of pervasive sensors too. Related proposals are analyzed in Section 3.3.

Similar to the third view, we consider system build over brand new socio-pervasive infrastructures, typically on an application-specific basis (oval D in Figure 2). Such socio-pervasive infrastructures thus act as the medium in which integration between the social and the pervasive sensors take place. Proposals in this direction are analyzed in Section 3.4.

3.1 Extracting data from social networks

As stated above, some proposals focus on extracting information from social networks and digesting them to produce knowledge that can be eventually exploited in pervasive services, as if such social sensing knowledge were at the same level of pervasive sensing one.

Gupta *et al.* (2012) propose PeerSense a system enabling context-aware services for people in short proximity in the physical environment (i.e. contextual photo-sharing, file sharing, etc.) where social networks are mined to gather social relationship between people. From friendship relations and privacy policies on the social network side, PeerSense serves as enabler for services between co-located people.

Shankar *et al.* (2012) present SocialTelescope, a location-based pervasive service that automatically compiles, indexes and ranks locations, based on user interactions with locations in mobile social networks. SocialTelescope location-based search engine uses geotweets by Twitter users to learn about places.

Ji *et al.* (2009) report a work on mining famous city landmarks from blogs for the provisioning of pervasive services based on personalized context-aware tourist suggestions. Their main contribution is a graph modeling framework to discover city landmarks by mining blog photo correlations with community supervision.

Zhao *et al.* (2006) propose ad unattended and context-aware service for detecting and framing events from the real world by exploiting the tags supplied by users in Flickr photos. The temporal and locational distributions of tag usage are analyzed, tags related to a periodic events and those of periodic events are distinguished. Tags are finally clustered and, for each cluster, a representing picture and tag is extracted. From such information context-aware services for events detection and listing are realized.

Lovett *et al.* (2010) present two heuristic methods for data fusion that combine the user's personal calendar with social network posts, in order to produce a real-time pervasive multi-sensor interpretation of the real-world events. This study shows that the calendar can be significantly improved as a pervasive sensor and indexer of real-world events through data fusion.

From our side, we have developed two unattended systems to extract information, respectively, from Flickr and Twitter social networks. The first one (Mamei *et al.*, 2010), accessing up-to-date and spontaneous information embedded in Flickr pictures makes context-aware recommendations to people visiting touristic places for the

first time. The second one (Ferrari *et al.*, 2011) presents an approach based on a probabilistic topic model (Latent Dirichlet Allocation) applied to messages from the Twitter social network. In this paper, the automatic extraction of urban patterns and people recurrent behaviors paves the way for pervasive service based on the predictions of events happening in the urban environment, as those for managing traffic congestions, realizing crowd displacement, managing calamities, etc.

3.2 Exploiting existing social networks as a socio-pervasive middleware

Proposals in this area consider social network infrastructures as a sort of socio-pervasive middleware in which to merge and consolidate data from different sources, specifically pervasive sensors, and from which to exploit the functionalities for data and event management.

Demirbas *et al.* (2010) have designed and implemented a crowd-sourced sensing and collaboration service over Twitter, for two application scenarios: a crowd-sourced weather radar, and a participatory noise-mapping application. The whole system is based on the intuition of exploiting Twitter as a publish-subscribe system for the storing and the diffusion of information and events about pervasive sensors and user-provided sensing data.

S-sensors (Baqer and Kamal, 2009) provides a framework to globally share locally measured sensory readings. This authors propose to employ micro-blogging to publish and share sensory data and resources, where short messages depicting the status of the environment are used to convey sensory data of the physical world. Here, sensor networks may utilize social network tools to distribute the sensing responsibilities amongst the networks.

Patterson *et al.* (2009) present a prototype system that automatically infers users' place, activity, and availability from sensors on their handheld devices or laptop computers. Data is then reported to buddies through embedding information in commercial instant-messaging profile status.

Treiber *et al.* (2011) present Tweetflow, a platform for collaborations of human and software services, for the execution of single workflows. Using tweets as communication messages, Tweetflow exploits Twitter social network infrastructure and existing tools. Exploiting the network structures originating from Twitter follower, Tweetflow can discover (human and software) resources that are required for the execution of a workflow and monitor the execution of workflows, simply by following workflows' tweets.

3.3 Pervasive overlays on social networks

Proposals in this area are related to interconnecting and sharing data sensed from personal devices with other entities or services in the web. Accordingly, software overlays over existing social networks infrastructure are realized to interface with such local networks and, to support specific application requirements, implement or extend existing functionality.

SenseFace (Rahman *et al.*, 2009) is a software overlay suitable for capturing the sensory data produced from user personal devices, processing and storing the sensory data in his/her personal gateway (which is a mobile device) and sending the data to a remote internet gateway. Finally, the sensory data is disseminated to a list of his/her social networks.

Anwar *et al.* (2005) propose an overlay constructed on top of the Orkut social network. Their aim is to demonstrate that an alternative model to query the social network, where each node chooses its peers to query using metrics that can account for data coming from pervasive sensors, not only improves the overall search time but also gives a sizable improvement in lookups, average round-trip delay and scalability.

Bauschlicher *et al.* (2011) propose a system called HatterHealthConnect (HHC) that combines the mobility and monitoring of a body sensor set work with the interaction capabilities of social networks. Basically, HHC is a software overlay fetching user health/sensor data and sharing health related data with other users on traditional social communities. By creating peer groups with similar disease, HHC can help to motivate and encourage each others, promoting users physical wellness.

Rahman *et al.* (2010) present a context-aware social network framework that can dynamically mash-up user sensory data and social networks. SenseFace provides facilities to push sensory data collected from user personal devices to the members of social networks, further providing real-time query of any sensory data by any authorized member of each social networks.

CoCo (Lane *et al.*, 2011) is a learning software overlay that exploits social networks to selectively combine small contributions of labeled data from people with shared context or user characteristics. Under CoCo a personalized classifier is trained for each individual user, but by exploiting social networks, the burden of providing training data can be spread over the entire community.

From our side, in Castelli *et al.* (2012) we present the solution adopted in the SAPERE middleware, a pervasive overlay network for the provision of pervasive service and applications. Our proposal exploits the graph of a social networks, and combines it with relations deriving from spatial proximity, to drive the topology of interactions among users, devices and services.

3.4 App-specific socio-pervasive networks

Here, the common idea of the analyzed proposals is to create brand-new application-specific network infrastructures (typically through mobile *ad hoc* networks), and related logical layers, as the *locus* in which socio-pervasive information exists and is made available to specific pervasive services.

Automated Murmurs (Freyne *et al.*, 2009) presents a mobile platform which leverages the popularity of mobile and social computing to produce a location-sensitive messaging system which delivers user generated content to the public on the basis of both physical location and social relations.

Beach *et al.* (2010) propose a system called SocialFusion for fusing mobile computing, social networks, and user personal sensors to promote socially-aware diffusion of information and events. A multi-stage architecture is proposed, in which issues of collecting and managing diverse data streams, mining the data for context-aware inferences of individuals and groups, and preserving privacy and anonymity, are addressed.

Olgun and Pentland (2008) present the design, implementation and deployment of a wearable social sensing platform that can measure and analyze personal and social behaviors in a variety of settings and applications. Individual and social patterns of behavior are identified measuring face-to-face interaction, conversational dynamics, physical proximity to other people, and physical activity levels.

The approach of integrating real-world data from face-to-face proximity with identities in on-line social networks, has been also followed by Van den Broeck *et al.* (2010) who have developed an application to for people attending scientific conferences. Personal profiles of the participants are automatically generated using several Web 2.0 systems and semantic data sources, and integrated in real-time with face-to-face proximity relations detected via RFID badges.

Diaspora (Bleicher, 2011) is a platform for implementing a distributed social networking service. Open source, free to use (but still in beta testing), Diaspora allows users to set up their own social profile on their own server (or "pod") to host and receive contents from third party information source or services, there included contributions from existing pervasive services and/or devices. The distributed network sees pods interacting to share status updates, photographs, and other social data with a special care on privacy issues.

WikiCiti (Resch *et al.*, 2008) is an application that both feeds and absorbs information from a network of citizens, to inform themselves about certain events taking place in the city. Citizens can retrieve real-time information related to the events such as nearby happenings, availability of public transportation, and traffic conditions, or create a personalized event route.

With similar goals, the commercial application Macrosense[6] is a mobile application that exploits the network it builds within its customer to provide them with relevant recommendation, personalization and discovery services. From the same company, CitySense[7] is another mobile service for real-time nightlife discovery and social navigation, answering the question, "Where is everybody going right now?" Both these two software are still in beta development.

4. Challenges and open issues

Despite many of the approaches in literature have been worked out in research projects and some of them have been tested with simple prototype systems (Miluzzo *et al.*, 2008; Ziv and Mulloth, 2006) combining social sensors and pervasive services still sees several challenges to be faced.

On the one hand, turning social networks into plug-and-play social sensing devices for future pervasive computing applications definitely asks for a deep rethinking (in terms of architecture and role) of both social networks and pervasive infrastructures. On the other hand, the use of the information coming from social network applications in pervasive services requires mechanisms to extract meaningful data, usable by applications and services (other than being readily understandable by humans), from the myriad raw facts and data produced by social and pervasive sensors.

In this section, we discuss the research open issues behind the realization of a seamless integration of social sensors and pervasive services. While some of these are already present in pervasive computing and context-awareness literature (Mehmood *et al.*, 2009; Aggarwal and Abdelzaher, 2011), they tend to be exacerbated with the integration of social networking platforms since:

- The data is often in free-text with no structure nor codified semantics, thus complex to process and understand: in a word this poses a problem of information understanding.
- There can be no guarantee on trustiness and delivery of specific information about specific facts and at specific times by social sensors.

- Social sensors are completely out of the control loop of system managers and application developers.

In short, the people behind social sensors can post whatever (even incorrect) information in whatever format, or simply not post anything at all.

This section ends with a discussion summarizing the link between the above social data intrinsic limitations and the identified open issues behind integration (Table I).

4.1 Modeling framework

While current social services are actually developed along application specific requirements and specifications, future social services should be constructed on the basis of common and re-usable tools and mechanisms. In particular, what is still missing is a general modeling view to frame data together whatever the source of information is a pervasive sensor or a social one. This framework should be able to manage data's spatial and temporal dimensions, and allow context-aware services to operate upon it.

In this field Padovitz *et al.* (2008) propose a context model describing context and situations using geometrical metaphors and concepts from the states-pace model. The authors, by developing a context spaces algebra, argue to be able to merge and reconcile existing views over context and to enhance the outcome of reasoning process. Between the many approaches in literature (Henricksen *et al.*, 2002), STEvent (Lauw *et al.*, 2010) represents an interesting model for the identification of events and situations happening between members of a community. Following the graph theory, they build a model for event extractions around the idea rather than events and situations about people can be derived from the graph-links among them.

4.2 Unified data representation and interpretation

Dealing with events, locations, date, etc. cannot neglect a shared vocabulary (that is, the type of objects and/or concepts that exist, and their properties and relations) used to model a domain. The vocabulary should be able to cover a wide range of concepts (events, locations, dates, etc.). This representation should avoid complex and highly-structured formats that would be difficult to be encoded and maintained.

An interesting research direction consists of the use of pragmatic (i.e. tag-based) ontologies to encode such diverse information. This comprises both an effective creation of such descriptions and an effective use by applications (Robu *et al.*, 2009). Their integration with shared vocabulary represents a challenge for future research. Ultimately, this problem boils down to natural language processing and it is even more exacerbated by the peculiar (and evolving) languages used in social network sites.

In addition, to better interpret such complex data, visualization techniques and tools should be developed. Data visualization tools can be the user interface to certain

Table I. The link between integration open issues and intrinsic social sensor challenges

	Challenges	
Understanding	Trustiness	Control
Unified data repr.	X	X
Model. framework	X	X
X	Data reconc.	X
X	X	Privacy concerns

applications, and they could become a core asset to see and understand the data produced by social and pervasive sensors at multiple levels of granularity. Works like Situvis (Clear *et al.*, 2010) represent an important step in this direction.

4.3 Data reconciliation and uncertainty

From our analysis, the majority of works in literature recognizes the potential benefits of cross-analyzing and cross-checking pervasive sensor data with information from social networks. However, most of the existing inference, correlation, or matchmaking approaches so far are quite limited and concentrate at a few purposes: discovery/suggestion of new potential social ties, recommendation of places to visit, detection of social events/crowding, inference of user (group) motion pattern; sharing data about the physical environment.

The key problem of all the above researches is that they are often conducted as stand-alone data-mining exercises and seldom exploited in a synergetic way. Instead, the real challenge is to integrate several techniques and have them cooperate in their inference activities. The point is that the knowledge that can be inferred from a multitude of different sensors can be more expressive and high-level (other than overall more correct) than that inferred by independently working sensors. For instance, if a body-worn accelerometer detects a "cycling" activity and the geo-coder detects the user is at home, the activity can be more properly corrected as "using a fitness cycle".

In any case, before social networks can widely contribute to the mining process, they have to reach a critical mass of data across many (i.e. spatial) characteristics. For instance, in our experience on Flickr (Mamei *et al.*, 2010), only a restricted number of cities in the world already have enough information to make our tourist recommendation tool applicable.

4.4 Privacy concerns

Handling privacy issues is a general problem related to pervasive and ubiquitous computing that is further exacerbated when social sensing is involved.

Despite the fact that people consciously agree to both providing their personal data and to being tracked by social networks services (i.e. many social networks utilize localization services) once information is uploaded, users complete lose any control of it. Once an information get the internet world user cannot get it back. This loss of control is especially noticeable in the case of social network sites, whose terms and conditions generally state that by the act of uploading information, users are allowing the company control over that information. This imply that new rules for respecting and preserving overall user privacy have to be formulated. In Chen and Rahman (2008) the authors investigate current mobile social networks and identify their weaknesses and strengths. From another side, aggregating and anonymizing data can provide a useful rough solution (Shi *et al.*, 2010).

Our idea is that privacy management should apply at different levels of content information, from single personal contextual information, to aggregated one, to inferred above. Thus, the issue of defining proper privacy policies for information in both social sensors and pervasive services is a complex open issue, involving:

- the different levels at which data is processed;
- the definition of privacy boundaries reflecting tension between the conflicting goals of enabling services while keeping confidentiality; and
- human-values to avoid unethical situations and bias.

In summary, privacy management requires a user to be conscious of what data he really wants to share, but in the presence of multiple and dynamic data sources, and different level of data granularity, reaching such a level of consciousness is far from being easy. In addition, since the pervasive application will be able to infer and aggregate information, the issue of understanding what information can be produced at the various levels of the privacy, and controlling how to share it, further complicate the control over it.

4.5 Discussion

Building towards proposed open issues assumes a twofold importance, since their overcoming not only would ease a seamless integration of pervasive and social services but also lead toward a better exploitation of emerging social sensors.

Table I shows the links between social data intrinsic limitations and the open issues for integration discussed in this section or, in other words, which social data limitations would benefit from advancements in which of the open issues. Consider the fact the social network messages are typically written in free-text and most of the time the content of the message could not be easily understood by a machine reading the message. This situation would definitely benefit from the presence of a shared vocabulary (from the unified data representation open issue) providing support to disambiguate the message content.

If this process would fail, the introduction of a modeling framework, able to organize information on both spatial and temporal dimension, would open further analysis dimensions (other than message content) enabling for the research and identifying of events and situations from data occurrences in space and time (Lauw *et al.*, 2010). Again reconciliation algorithms, cross-checking social data with data from other sources, would definitely improve social data trustiness, as well as the definition of privacy rules would ease the control and management of exposed information.

5. Conclusions

In the next few years, social networks will increasingly contribute to enhance the functionality of pervasive computing services. In fact, while pervasive computing services already intensively exploit ubiquitous to promote some context-awareness, the possibility of exploiting also social networks as sorts of social sensing devices, will make it possible to deliver highly-adaptive socially-aware, other than simply context-aware, services.

In this paper, having argued the importance of exploiting social networks as sorts social sensing devices, we framed and described the possible approaches to integrate social networks and pervasive networks, surveyed relevant proposals in the area, and discussed the open research issues to be faced to make such integration possible and easy to use.

Our current research work in the context of the Self-aware Pervasive Service Ecosystems (SAPERE) Project is aimed at identifying general solutions for the exploitation of social sensing data in pervasive service infrastructures, so as to make services highly-aware of their context of usage and self-adapt accordingly.

Notes

1. Google trends site: www.google. com/trends
2. Tweetronics site: www.tweettronics. com/

3. Google Latitute site: www.google.com/latitude
4. Traffic Aus site: http://itunes.apple.com/au/ app/aus-traffic/
5. Waze site: http://world.waze.com/
6. Macrosense site: www.sensenetworks.com/macrosense.php
7. Citysense site: www.sensenetworks.com/citysense.php

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