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On The Design Of An Intelligent Sensor Network For Flash Flood Monitoring, Diagnosis And Management In Urban Areas *Position Paper*

M. Ancona[a,*], N. Corradi[b], A. Dellacasa[a], G. Delzanno[a], J.-L. Dugelay[c], B. Federici[d], P. Gourbesville[e], G. Guerrini[a], A. La Camera[a], P. Rosso[f], J. Stephens[g], A. Tacchella[a], G. Zolezzi[h]

[a]*Dipartimento di Informatica, Bioingegneria, Robotica e Ingegneria dei Sistemi, Università di Genova, Via Dodecaneso 35, I-16145 Genova, Italy*
[b]*Dipartimento di Scienze della terra, dell'ambiente e della vita, Università di Genova, Corso Europa 26 I-16132 Genova, Italy*
[c]*EURECOM, Campus SophiaTech, 450 route des Chappes, F-06410 Biot., France*
[d]*Dipartimento di Ingegneria civile, chimica e ambientale, Via Montallegro 1, I-16145 Genova, Italy*
[e]*Laboratoire Innovative CiTy (I-CiTy URE 005), University of Nice-Sophia Antipolis, Nice, Provence-Alpes-Cote d'Azur, France*
[f]*PRHLT research center, Universitat Politècnica de València, Camino de Vera s/n. 46022 Valencia, Spain*
[g]*MJC2, 33 Wellington Business Park, Crowthorne, Berkshire, Rg45 6Ls, UK*
[h]*Dipartimento di Ingegneria Civile Ambientale e Meccanica, Università di Trento, Via Mesiano 77, I-38123 Trento, Italy*

Abstract

We propose an intelligent sensor system based on a new sensing methodology, relying also on 3D map reconstruction techniques, for computing with high precision, in real-time and without human intervention the parameters needed for stream-flow computation: water levels, morphology of the streams of all potentially flooded areas by each controlled stream. The collected data will be continuously transmitted, through a communication infrastructure, to software agents designed to compute the stream-flow and to quantify the spatial distribution of flood risk for each controlled watershed. The computed risks, together with other data coming from other sources (barometric sensors, camera operators of public organizations, emergency agencies, private citizens), will be analyzed by a diagnostic decision system implementing a risk-alert scheduling strategy. This system will be able to diagnose the health state of the controlled environment and to define specialized alarm levels for each potentially interested area that will be used to alert all citizens (ubiquity) locally present (alerting locality).

Keywords: Intelligent Sensor Network; Flood Monitoring; Sensor Fusion; Social Sensing; Data Integration; Real-time Warnings; Geo-referenced communication.

* Corresponding author. Tel.: +39-010-353-6605 ; fax: +39-010-353-6699.
E-mail address: massimo.ancona@unige.it

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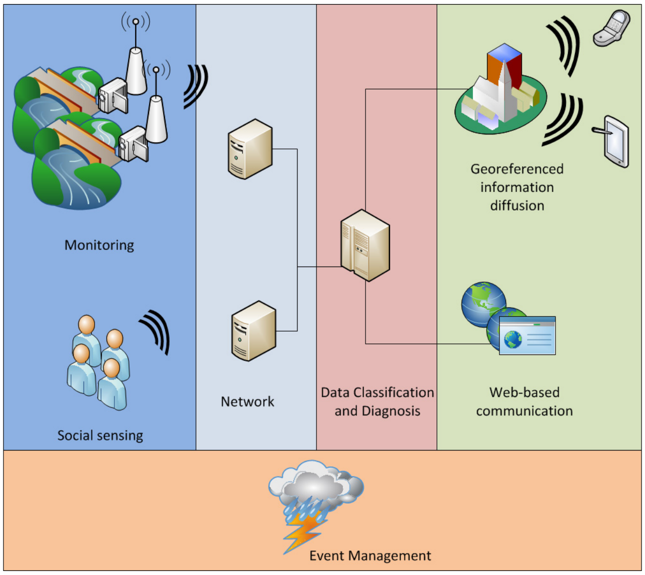

Fig. 1. The main components of the architecture of our intelligent sensor system.

1. Background and Motivations

Recent studies on climate changes in Europe show an increased frequency and intensity of heavy rainfalls and flash floods in urban areas. In France, Spain, Italy, and in particular in different Ligurian areas including Genoa, an important fraction of the population lives in areas potentially subject to floods. To reduce the effects of natural events, accurate models of the dynamics of flash floods should be integrated into new public alarming infrastructures[6,13,10,4,21,22,23,24,25,26]. In urban areas like Genoa the solution is particularly difficult, because of the combination of several factors including a complex conformation of the urban territory presenting a large number of rivers and creeks with steep or covered watershed and buildings not complying with safety measures.

All the above mentioned ingredients make the lag-time occurring between a rainfall peak and the corresponding discharge peak extremely small, leaving almost no time for effective human intervention in the alarm and risk alert detection process.

In order to attack this problem, in this paper we propose a solution based on Intelligent Sensor Systems for flash flood warnings. Our approach is centered on a new way of computing with high precision, in real-time, and without human intervention, the discharge stream flow (i.e., the volume of water that moves over a designated point through a fixed period of time). The computation is done by combining different types of low cost sensor devices (IMUs, Laser scanners, stereo cameras) such as those used in recent approaches in 3D map reconstruction with robots[5]. The resulting data are meant to be fused together with other sources communicated by different types of agents (existing monitoring stations, data coming from social sensing). Data fusion and classification will be performed by using advanced semantic web methodologies and services. Standards defined in the context of the Semantic Sensor Web initiative[12] can be applied here for collecting, integrating and comparing information coming from different sources.

All resulting data will be transmitted in real-time through a wireless communication infrastructure in order to estimate the lag time between the maximum rainfall and the discharge peaks and to determine the danger level and its maximum peak time expectation.

Warnings and relevant information will be spread via all the exploitable media, in order to reach the highest number of people: web portals, mobile applications, satellite and cellular phone networks, digital TVs, with specific reference to individuals within the range of critical areas (geo-referenced communication).

In the rest of the paper we will give a more detailed description of the overall architecture and of its individual components. Our goal is to obtain a modular architecture that could be open to extensions both from what concerns the sensor/actuator interfaces and the decision support systems.

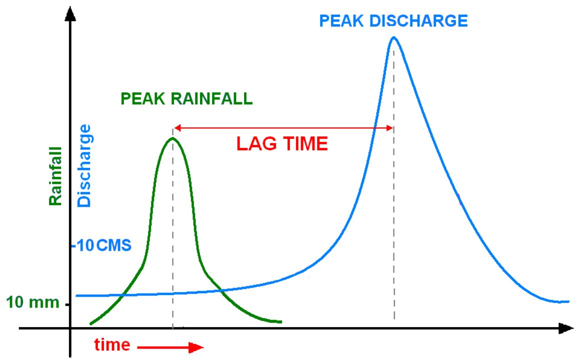

Fig. 2. Lag time is defined as the time interval from the central peak of rainfalls (shown in green curve) to the peak of the resulting discharge of the stream (shown in blue curve).

2. Overview of the System

The overall architecture of our Intelligent Sensor Network, see Fig. 1, is based on the following components.

Monitoring. We can divide sensors in rainfall monitoring and water discharge monitoring. They can be used for determining their mutual temporal correlation (called lag time and described in Fig. 2). Concerning rainfall monitoring, several networks exist worldwide and, in particular, we plan to use data coming from the Ligurian Regional Systems[27,28]. Furthermore, we are interested in the fusion of data coming from the following types of sensors:

- Traditional instruments (e.g., radar and infrared based instrumentation, flow meters, etc.) for measuring water level and flow velocity where available[21,22,24].
- Instrumentation used for 3D map reconstruction[5] like laser scanners (LiDAR), IMU, RGB-D sensor, etc.

In general we tend to prefer non-contact sensors[25], that are maintenance-free and more reliable. Indeed, direct-contact sensors permit better measurements, but they could have low expectation to survive to the strong floods of most steep streams of Liguria. The devices resulting by the sensor fusion can be either mounted on a fixed installation or on a flying vehicle for rapidly changing the observation point. The device is applied to watershed reconstruction during dry periods (e.g., to collect precise data about the watershed contour, section, depth, etc even in the proximity of buildings) or for real time capture of water levels and flow velocity during rainfall. We will give more details on possible instrumentation that can be considered in this context in Section 3.

Social Sensing. Another important source of information comes from social data. For instance, services like Ushaidi, Crowdmap, SwiftRiver[19], developed in different areas like electronic elections, can be used to collect geo-referenced data from citizens. More common web services like YouTube can be employed to extend information to video and images. Reputation-based mechanisms, natural language and image processing methods can be applied here for extracting and filtering this kind of data sources.

Network, Nodes and Communication. Each sensor node will be equipped with different types of communication devices in order to be able to detect and to connect to available wi-fi, cellular and satellite networks. Communication interfaces are available in the market providing fault tolerant communication systems. Microcontroller and low cost processors like Arduino can be employed in order to physically connect different types of sensor devices within a single sensor node (i.e. to implement in place data aggregation). Thanks to the upcoming 4G wireless communication networks, it would be possible for a drone to transmit videos of high quality in real time and also to receive control commands from a remote base station much more efficiently than with current networks. That would allow us to develop new services attached to mini drones for floods control in urban areas.

Data Classification and Integration. In order to design an open-ended and modular application in which to integrate new sensors as soon as they become available, it is critical to be able to provide interchange data formats for achieving high levels of interoperability, e.g., between different sensor and actuator nodes. This goal can be achieved relying on semantic web methodologies. Namely, the key point is the application of Ontologies for the specification of heterogeneous data, together with the use of data exchange formats designed for sensors like O&M and SensorML (standard models and XML schemas encoding, resp., measurements and sensor systems), and standards for web services like SemSOS defined by the OGC-SWE group in order to standardize the way sensors and sensor data are discovered and accessed on the Web. They are part of the Semantic Sensor Web paradigm [16,15,12] that also includes standard web service interfaces for publishing and subscribing to alerts from sensors (SAS, Sensor Alert Service) and for asynchronous delivery of messages or alerts (WNS, Web Notification Services). These standards are defined on top of powerful modeling and query languages like RDF-OWL and SparQL [17,18]. Furthermore, techniques for processing queries over streaming data, allowing to cope with Big Data "velocity", can be applied here in order to filter, compare, and match heterogeneous data (expressed in a common idiom). In this way, we will be able to process data as soon as they become available and store them for successive elaborations only relevant information. This approach to data management is well suited to integrate social data, that naturally come in as a stream, out of which only relevant items need to be considered. Another important aspect is to design bi-directional information flow between perception and analysis, in order to dynamically improve filtering and selection capability of sensor nodes.

Diagnosis and Validation. This module implements real-time monitoring and diagnosis after data fusion and filtering. The key point here is to define rapid and precise analysis to determine and to dynamically adapt alarm levels and warning notifications. Rule based systems, e.g., equipped with uncertainty weights and semantic information coming from the domain under consideration, can be applied for real-time diagnosis. Automated reasoning methods developed in the field of Artificial Intelligence (e.g., diagnosis, planning, scheduling under uncertain knowledge using logic-based methods and tools) seem well suited for this task thanks to their natural predisposition for modular reasoning, an important feature during the development of prototypical systems. Validation methods based on models like communicating and time automata, Petri nets or graph transformations can also be employed for ensuring the quality of the considered distributed systems and protocols [3,1].

Geo-referenced Warnings. A fundamental part of the architecture is the support for geo-referenced communication of real-time warnings, and, more in general, of information related to flash flood management. Cellular and satellite networks can be used to notify warnings, e.g., via SMS or email sent to (registered) citizens living or working in the surroundings of a critical area. Geo-referenced notifications are important for at least two reasons: to avoid unnecessary alarms in non critical areas and to obtain a more flexible adaptation of warning notifications (it can be changed more rapidly without provoking confusion or panic situations in the entire population, if restricted to a limited area and a set of citizens). The same methods can also be applied for other types of information, e.g., road signals, that can be made more accurate for restricted areas.

Web-based Communication. Web-based portals (again by exploiting services like Ushaidi [19]) and mobile applications with geographical systems (e.g. Android, Google Maps, Open Street Map) play an important role for the diffusion of all other type of information that can be useful for citizens and local authorities, such as hydrological risk maps, geo-referenced historical data, and statistical analysis. Concerning the communication infrastructure, it could be quite useful to develop web-based software platforms that can be used to design customized web portals, following examples of Content Management Systems (CMS) such as Moodle and Joomla, that can be adapted to different types of end-users. Another important aspect is the design of visualization methods for the collected data (e.g., via geographical servers or graphics and diagrams designed for Big Data) that can be adequate for the analysis of large amount of data for both specialists and non-specialists end-users.

Event Management Processes. An orthogonal, but equally important, aspect of the architecture is the design of modules for supporting planning and scheduling activities related to the entire process of monitoring, prevention and event management. The systems should provide platforms for programming strategies and automatically generating plans for dynamic reconfigurations of road traffic, food supply chains, public transportations, emergency vehicles routes, people evacuation, etc. This kind of services could be provided in form of specific modules in order to be activated in response to detected alarm situations. Web-based platforms could be provided to local authorities to define workflows and planning activities in emergency situations.

3. Sensor Fusion for a Closed-loop Warning Infrastructure

In this section we focus our attention on the problems related to the design of a closed-loop infrastructure for real-time warnings, a challenging problem for flash flood monitoring. For this part of the proposed architecture we will describe and compare different types of sensor devices.

The warning system is centered on the correlation between rains and the peak discharge. The problem of obtaining an adequate rainfall distribution is considered by using public services available in our region combined with low cost technology based on satellite antennas and GPS receivers. For a significant test case, a sufficient number of rain gauges (pluviometers) will be installed (in Liguria we have a mean number of 1-2 gauges for a small stream and of 5-10 for a larger creek).

The sensor we are designing integrates existing devices with new instruments based on advanced technologies used in robotics for map reconstruction[5,2] like visual, photo sensors, IMU, barometric sensors etc.

For example, concerning laser scanners used in robotics, the small-size and lightweight (160g) Hokuyo URG-04LX-UG01, with a cost around 1000€, has a good resolution (1mm resolution in a 240° arc) and range (from 20mm to 5.6m). Indeed, its power consumption (5V, 500mA) permits a use in battery operated platforms. Other interesting low-cost devices are the ones used for video-gaming like Microsoft Kinect. Kinect is equipped with a motion detection software but it has limited precision (12mm at 2m). Its performance in outdoor applications are for the moment very poor.

Although the degree of topographic model complexity needed to achieve a significant improvement in urban flood modelling is still a matter of research[8]. In urban contexts a special role is played by high-resolution LiDARs as mentioned in[26]: *"Features like buildings, constructed river banks or roads have a great effect on flow dynamics and flood propagation and only high-resolution input data can solve the purpose that relates to the systems topography* ...omissis... *Differences of a few meters can means a lot in loss calculations in urban areas. LiDAR has brought this level of detail to the industry allowing for much more accurate flood prediction models to be create"*.

The designed sensor should be either mounted on a fixed installation or on a flying vehicle (a suitable mini-drone costs about 1000€) for rapidly changing the observation point. The integrated device can be applied both for watershed reconstruction during dry periods (e.g., to collect precise data about the watershed contour, section, depth, etc) and in real time during critical events as an additional automated support for operators working in the area under observation (e.g., to collect data for post-event analysis). In[11], the authors developed algorithms for 3D reconstruction using video recorded by a single quadcopter's frontal camera. Based on a corkscrew flight and on the matching of a few hundreds of distinct image points between consecutive frames, a sparse 3D reconstruction of the recorded scene is possible. For a dense 3D reconstruction, it is possible to simulate a stereo vision system by a vertical offset motion. Nevertheless, some limitations exist due to the maneuver duration that takes about half a second.

Below we briefly discuss advantages and drawbacks of fixed and mobile installations. A fixed sensor can be mounted on a pole or on a building close to the stream. It operates in two different modes:

- during dry periods, when the flow stream is almost empty. In this first configuration the device computes a detailed stream bottom contour section with a laser sensor (for example, by dividing it in subsections and calculating the geometrical parameters of each one).
- during rain storms, when the flow level becomes to be relevant. In this case other devices, like increasingly available and relatively cheap portable radar devices[14], are activated for measuring water level, flow velocity (of the whole section or per subsection depending on the size of the stream) and automatically implementing a flow measurement mechanism based, for example, on the Sum of Partial Discharges Protocol or adopting an equivalent method.

Other relevant parameters to consider are those related with the transport of sediments and of large debris which highly affect the damaging potential of a flood event. In general, fixed sensors have the advantage of not requiring human intervention and of being protected in difficult circumstances while the mobile (flying) ones offer the advantage of cost reduction, because they can cover a large part or the whole stream, but they require an operator and are critical in difficult weather situations. A mixed approach seems to be more convenient, because stream scanning performed during the long periods of flow inactivity is not required to be performed in real-time and drones are perfect for this task, while the other measures must be performed in real-time during rain storms and a protected and fully automated approach is preferable.

4. Conclusions

We presented the design of an intelligent sensor network for instrumenting streams in urban areas. While rainfalls are sufficiently monitored by networks connecting a large number of sensors, in general, streams and creeks are instrumented with an inadequate number of devices. This fact is due to the higher complexity of the relative data acquisition problem. On the other hand, high resolution data are required while a limited number of parameters can be realistically computed in an closed loop, without human intervention. Our strategy lies in the capability of designing a set of sensors able to acquire the minimum set of input data needed to grant a reliable forecasting of alarms. In particular, we expect a considerable improvement of the ability to predict the spatial dynamics of urban flooding and therefore to minimize false alarms and to forecast events with acceptable approximations.

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