Metrological Characterization and Semantic Annotation of Space-Aided Distributed Sensor System for Hydrogeological Disaster Management

Gregorio Andria / Eugenio Di Sciascio / Anna M. Lanzolla / Michele Ruta
Dept. of Electrical and Information Engineering – Politecnico di Bari
Via E. Orabona 4, Bari, I-70125, Italy
e-mail: gregorio.andria@poliba.it / eugenio.disciascio@poliba.it / anna.lanzolla@poliba.it
michele.ruta@poliba.it
Sabino Cacucci
Leonardo S.p.A.
Viale del Lavoro 101, Taranto, I-74123, Italy
e-mail: sabino.cacucci@leonardocompany.com

ABSTRACT

In a disaster or generally in a critical event, the availability of innovative, space-based autonomous sensor network systems used as support for the "early warning" of the event, is strongly recommended. This paper deals with a discussion on behavioural development of such systems, devoted to improve the effectiveness of their "first response". It is envisioned how a suitable metrological characterization of sensors could be enhanced by a semantic characterization of raw data in order to enable logic-based inferences. The resulting system allows a robust improvement of performance and reliability with respect to competitor frameworks. Both ideas and approaches are now implementing in an off-the-shelf publisher/subscriber Message-Oriented Middleware named BEE-DDS in order to assess feasibility. Tests and experiments are underway.

1 INTRODUCTION

Decision Support Systems (DSS) are considered of a particular relevance for hydro-geological distress prevention or even management. It is noteworthy the large the availability of data, in any place and under any meteorological condition, which can support decision-makers in assuming rapidly actions for protecting citizen. During these last years, many remote sensing techniques have been developed to monitor physical or environmental conditions (such as temperature, sound, vibration, pressure, motion or pollutants) in order to study climate changes and to assess hydrogeological disasters [1]-[6].

This paper presents a DSS providing assistance for the "early warning" of a disaster or critical situation and able to improve the "first response" to the happened event. It is based on the integration of satellite data (TLC, EO, NAV) and *in situ* information, exchanged following the innovative model of swarm intelligence. Information sharing is well suited to the design of complex knowledge-driven operational procedures, such as safety actions or disaster recovery, both based on the interaction of cooperative agents, *i.e.,* autonomous and auto-adaptive nodes following a goal realization in an evolutionary scenario [7] [8]. The envisioned system will provide:

- a natural Resource and Emergency Management and Organizations designated to answer to the first warning of a disaster and immediately after it;
- ICT-based methods and techniques to improve understanding of the natural disasters processes aimed at mitigating the damage;
- a Support Service able to provide mechanisms for early warning for crisis management.

The system design follows the objective of providing the *right* information in the *right* time to the *right* person to support the *right* decision. The information management process is critical: an end-to-end *Quality* *of Information* must be pursued; a continuous *Context Extraction* must be performed both in terms of: (i) the place where data are generated, and (ii) the place where the data are consumed. The system incorporates a swarm-oriented data distribution service which gathers environmental measures as sensor output, validates them after suitable metrological characterization operations, and annotates them in a machine understandable format and enables deductive inferences about not-evident and implicit information [9].

Each agent in the swarm aims at the provision of data referred to a specific item and/or subject of the natural resource protection process. The sensed information manipulation will be specifically designed to obtain a high informational added value w.r.t. the original raw data. A given informative service may be requested to the DSS by different actors, with a different operational objective each. A multi-purpose decision pipeline can be set-up in order to optimize performances in time-critical scenarios such the ones the system faces to. *Bee Data Distribution System (Bee-DDS)*, a message-oriented platform based on the publish-subscribe model, is the one adopted for the swarm setting. It provides affordable communication among loosely-coupled agents and nodes to support functionalities of monitoring, safety and recovery. The proposed framework results as a general-purpose infrastructure-less information sharing facilitator. It is exploitable in several different scenarios. The implemented prototype is under test in an extensive experimental campaign, aiming to verify correctness of the approach and obtain a preliminary performance assessment.

2 PROPOSAL ADDED VALUE

The proposed system, named SMART, aims at improving the quality of information to support (i) the plans addressing the management of disaster or critical event related to hydro-geological diseases and (ii) the "first response" to emergencies. The information management process must be carried out by always taking into account the end-to-end Quality of Information. Both (i) the context where data are generated and (ii) the context where data have to be consumed, *i.e.,* the user specific context, will be considered.

The proposed system exposes several Information Services each aiming at the provision of data about a specific issue of the natural resource protection process. The information provided by a generic Information Service is the outcome of a raw data processing specifically designed to obtain a high informational added value w.r.t. the original basic data. An Information Service may be requested by different actors, each with a different operational objective which requires different QoS contracts. An Integrated Information Service will decouple the Information Specific Services (namely *Landslide Information Service*, *Flooding Information Service* and *Field Information Service*), coming from the differentiated end user community, to allow for a diversified packaged information provisioning aiming at satisfying the all the needs of (very) different users, through the public bodies and instruments responsible for.

The envisioned system and the related services provide a meaningful added value for different categories of end-users as they fulfill key needs for hydro-geological distress, *i.e.,* the availability of data in any place and under any meteorological condition, to support the entities in charge of preventing and managing natural diseases. The QoI will be improved through the adoption of: (i) innovative methods and algorithms for early warning, such as the Landslide Information Services, and Flooding Information Services, and (ii) a data-centric architecture for the data distribution on the field for a better Situational Awareness and Common Operational Picture of all of actors involved in the management of a disaster. In addition, thanks to the adoption of advanced data-centric architecture models, the proposed solution has the great advantage of not interfere but only strengthen the procedures currently used by the Civil Protection to collect and manage the monitoring data. In what follows, some more details about the added value provided by each single service of the proposed system will be given.

Landslide Information Services added value. During these last years, many remote sensing techniques have been developed to study landslide events, but almost all of them concentrated on studying the causes of the event and effects after that it has occurred. The objective of SMART system is to apply different remote sensing techniques to detect precursor events for early warning of landslide risk. The implementation of this new precursor for landside represents an add-on for hydro-geological risk prevention with respect to the systems adopted up to now.

Flooding Information Services added value. The hydrometers used nowadays, are expensive and difficult to maintain, the HydroSat[1] sensor [13] could represent a good opportunity of extension of hydrometers network, although more limited in resolution, with reduced costs. The growth of hydrometers network can increase the precision in defining the intervention area impacted by flooding risk. The possibility to handle simultaneously warning indicator and gatherer data coming from peripheral sensors can facilitate the data management inside the complex network of Civil Protection to take proper decisions. It should be considered that currently many problems occur during emergency just for lack of information.

Field Information Service added value. During the first responder activities, very often there is a lack of updated information about the events and status in the operational area. The Field Information Service improves the Situation Awareness (SA) of the single operator and provides a Common Operational Picture (COP) to both the first responders operating in the field and the tactical and strategic control centers for a cooperative management of the disaster. They may improve the quality of the operators' decisions by providing them with QoI-based services.

The SMART service will adopt the Value Chain depicted in Figure 1 below, where main stakeholders are described hereinafter.

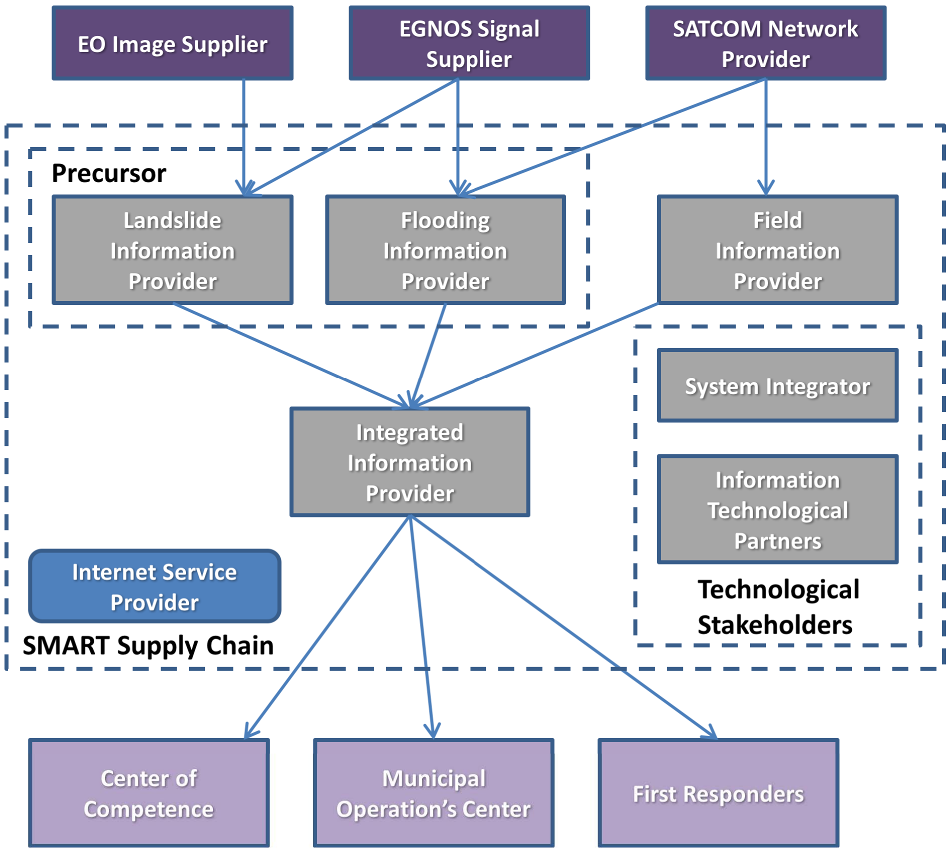

Fig. 1: SMART Value Chain

[1] Device of an instrument platform for hydrology, consisting in a multi-sensor satellite approach for the study of hydrological applications. These hydrology specific sensors are proposed to fill the gaps not covered by the current and planned systems.

The *Landslide Information Provider* takes EO data, the Cosmo-SkyMed products[2], and provides landslide precursor information as outcome of Cosmo-SkyMed time series and *Permanent Scatterers Technique*[3]. The *Flooding Information Provider* offers river flow information acquired via the Hydrosat sensors network which is based onto the EGNOS[4] positioning data. The *Field Information Provider* provides real-time data directly from the operational field and for the operator in the field via a network-centric, real-time middleware which integrates sensors and actuators. The *Integrated Information Provider* distributes packaged information, QoI-aware information flows specifically tailored for each (class of) end-user. Finally, the *Integrator* recalls information for the overall network-centric system upon which the SMART services are based. It also takes care of system maintenance and evolution. In addition, *Technological Partner(s),* supports a specific Information Provider with scientific, engineering, and system competencies.

3 PROPOSED FRAMEWORK AND ARCHITECTURE

Non-invasive solution with very low impact with a possible disaster scenario are strongly required, then the described SMART System has to be characterized by no interferences. For this purpose, the data-centric architecture featuring SMART is based on inter-node communication primitives implemented by *BEE Data Distribution Service*[5] middleware, which provides a suitable real-time distribution of information, due to the use of a right model of publishing/subscribing.

A lot of suitable rules and strict constraints have to be adopted to achieve timely and effective data delivery among network nodes of the whole system in every time and case. The above mentioned middleware could be employed in a wide range of applications including surveillance, crisis management, ground segments, logistics, smart cities control, air traffic management and many more.

The BEE Service includes the two components **D**ata **L**ocal **R**econstruction **L**ayer (DLRL) and **D**ata **C**entric **P**ublish/**S**ubscribe (DCPS). The first one enables an interaction interface between application objects and data coming from the second one, which defines entities, roles, interfaces and QoS policies for the platform of publishing and subscribing. In the off-the-shelf BEE DDS platform, service discovery is carried out via basic string-matching of topics, whilst the implementation of additional layers proposed later on aims to make BEE DDS middleware knowledge-oriented, in order to increase effectiveness and flexibility. The implemented architecture is focused on data as a primary asset and gives key quality factors as interoperability, adaptability, robustness and scalability.

The different components of the SMART system are very specialized devices and/or entities: people, sensors, software agents, smart devices, able to cooperate in order to adapt to the environment where they operate, very mutable depending on the various circumstances.

For example, a team of first responders can be supported by software agents hosted on personal smartphone/tablet acting as interface toward smart devices scattered throughout the area to be monitored. Then, these devices provide suitable real-time information to support the operations of the team and allow to

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2 Commercial products suitable for many remote sensing applications based on direct usage of other low level products. They are subdivided into various typologies: RAW data focused in slant range-azimuth projection, that is the sensor natural acquisition projection; Detected Ground Multi-look product, obtained detecting, multi-looking and projecting the Single-look Complex Slant data onto a grid regular in ground; Geocoded product, obtained by projections onto a regular grid in a chosen cartographic reference system.

3 Technique composed in general of: a systematic analysis of SAR data taking advantage of the available data set, the identification of single coherent targets only slightly affected by temporal and geometrical decorrelation (so called *Permanent Scatterers*), the estimation and removal of the Atmospheric Phase Screen (APS), and the extraction of the phase contribution due to target motion with high accuracy.

4 The European Geostationary Navigation Overlay Service (EGNOS), Europe's first venture into satellite navigation, improves the open public service offered by the USA's Global Positioning System (GPS).

5 BEE Data Distribution Service, a Leonardo Company product

respond automatically to commands issued by the team. The innovative elements of SMART system are represented by the dashed box in Figure 2. They provide additional capabilities resumed hereafter.

The Precursor area elements, which will feed the Precursor Information Services are:

- Permanent Scatterers, which use the EGNOS navigation services;
- Landslide Precursors, which use COSMO-SkyMed products;
- Flooding Precursors, which are based onto HydroSat, an innovative buoy that is based on the EGNOS navigation services.

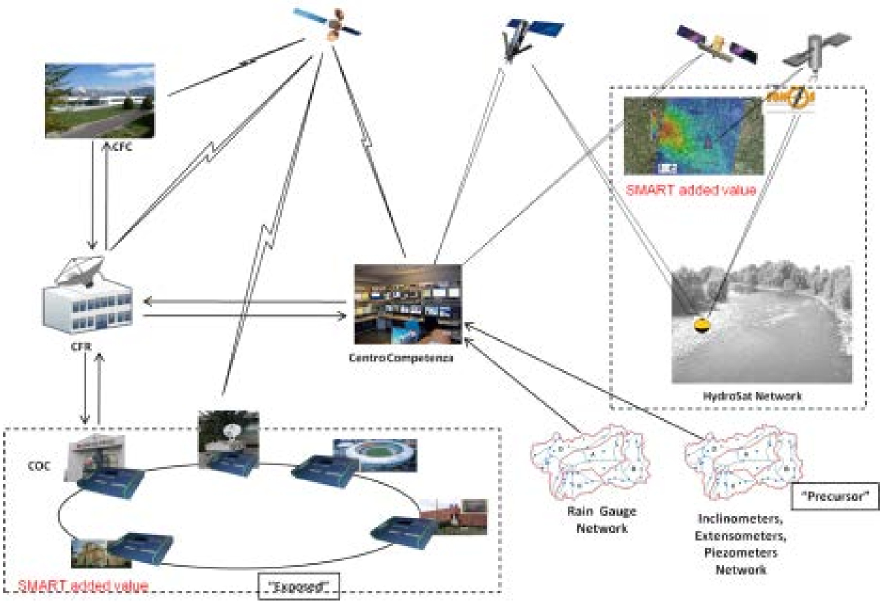

Fig. 2: SMART System Architecture

The Exposed area elements that will feed the Field Information Services are:

- The Adaptive Information System for Prevention and First Response (AISPR), which provides a data-centric information infrastructure. The node density and its autonomous, serverless cooperation capability make the AISPR system intrinsically robust, *i.e.,* it is able to provide the service even in presence of malfunctioning/faulted nodes. The AISPR is pervasive and allows sharing a comprehensive vision of the disaster phenomena, through the installation of BEE Sense nodes on each critical point to be monitored.
- BEE Sense, an innovative cluster of devices, both sensors and actuators, which acts as AISPR node supporting the personnel involved in emergency management via real-time data and ad-hoc effectors nodes.
- Smart personnel equipment, which assists the operator in the field by increasing his/her situational awareness via the real-time data provided by BEE Sense nodes, and enables the squad coordination via low bandwidth signals that do not impact the operator key senses, *i.e.,* sight and hearing.
- SATCOM node that extends the adoption of the data-centric architecture to remote control centers.

The use of the SMART system allows to deploy a more widespread network of sensors, even in the most inaccessible areas in order to reveal in advance the raising of the level of the river in areas near to the most densely populated urban zones. More extensive and timely information is made available to the various players involved through continuous and not interruptible communication. Therefore, it is possible to carry out the verification and updating of the risk status in a safer manner because the operational squads are sent to work with the most reliable information.

4 MULTIPLE SPACE ASSETS: PECULIARITIES AND NOVELTIES

The SMART system will be based on the following space assets: COSMO-SkyMed, EGNOS, TLC

Satellites.

The description of the above system satellites is avoided assuming that they are very well known. On the contrary specific satellites services, which will be used by SMART System, will be outlined in what follows:

- COSMO-SkyMed: the data and products provided by the COSMO-SkyMed system (http://www.cosmo-skymed.it/en/) represent valuable tools to carry out studies about causes and precursory phenomena of environmental disasters and to improve the capacity of monitoring and assessment. The continuous observation over time in a specific area, day and night, even under cloud cover, allows evaluating the surface deformation of the territory. COSMO-SkyMed provides what the current international context of Earth observation requires *i.e.,* information updated and available in time to make decisions faster and faster and adequate to meet the growing needs of civil protection.

- EGNOS: is the first European satellite navigation system (http://www.egnos-portal.eu/) which provides accuracy of the positioning signals sent out by GPS. It allows users in Europe and beyond to determine their position within 1.5 meters. The greater EGNOS precision with respect to the GPS allows tracking objects with better accuracy; moreover, it allows more accurate geo-reference map/images (*e.g.,* COSMO-SkyMed images).

- EUTELSAT Hot Bird (http://www.eutelsat.com/en/satellites/the-fleet/EUTELSAT-HB13B.html): is a group of satellites operated by Eutelsat (http://www.eutelsat.com/en/home.html), located at 13°E over the Equator (orbital position) and with a transmitting footprint on Europe, North Africa and the Middle East. The satellites are numbered 13B, 13C and 13D. Only digital radio and television channels are transmitted by the Hot Bird constellation, both free-to-air and encrypted. In addition, there are a few interactive and IP services. The satellites support bidirectional link via on board Payload SkyPlex within subnet SkyplexNet™ (*Telespazio*).

- IRIDIUM (http://www.marsat.ru/en/technologies-iridiumnetwork): is a large group of satellites providing voice and data coverage to satellite phones, pagers and integrated transceivers over Earth's entire surface. Satellites incorporate additional payload such as cameras and sensors in collaboration with some customers and partners. Iridium can also be used to provide a data link to other satellites in space, enabling command and control of other space assets regardless of the position of ground stations and gateways. The constellation will provide L-band data speeds of up to 1.5 Mbit/s and High-speed Ka-Band service of up to 8 Mbit/s.

5 UBIQUITOUS KNOWLEDGE BASE MODEL

The *Ubiquitous Knowledge Base* (*u-KB*) model [10] grants transparent access to information embedded in semantic-enabled objects scattered in a given environment (see Figure 3, representing the proposed DDS Layered Architecture). Foundations of such an approach are in the classical theory of Knowledge Base models in Knowledge Representation Systems based on Description Logics (DLs). A KB is composed by a

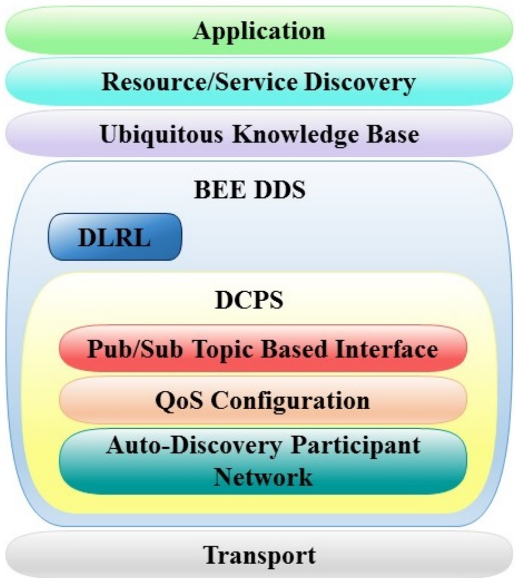

Fig. 3: DDS Layered Architecture

Terminological Box (TBox or *ontology*), *i.e.* the formal representation of the conceptual model of the studying domain through a taxonomy of *classes* and *properties* [11] and an Assertion Box (ABox) specifying the factual knowledge concerning a specific problem, with *individuals* as instances of classes. Software tools called *reasoners* allow to derive implicit knowledge from what explicitly stated in a KB.

In a u-KB, individuals are physically associated to distinct devices in a given environment (sensors, actuators, users). The ontology is fragmented in one or more *chunks* scattered across the network nodes. Different u-KBs can be managed by nodes in the same domain. The unambiguous association of every individual to its reference ontology is obtained via unique ontology URIs (Uniform Resource Identifiers). For a given reasoning task, the whole ontology is not typically required: in a u-KB, before starting inferences, the reasoner-equipped node retrieves only the ontology fragments necessary for reasoning based on classes and properties referenced by the involved resources.

Each of the nodes scattered in the environment manages a cache of ontology chunks. Every cache contains a static small part of the ontology (named Upper Ontology, UO) as well as the chunk(s) required by detained semantic service annotations. Before the further reasoning phase, a requester node must recompose a subset of the whole ontology and intercept all the classes associated with the proper ancestors engaged in the semantic descriptions in order to enable the matchmaking process. Hence, it sends a message with the *BuildTBox* topic containing: (i) the ontology URI identifier, (ii) the list of needed class IDs, and (iii) the topic name to subscribe for reply (*e.g.*, *MergeOnto*_NodeID). All nodes should be subscribed to *BuildTBox* topic. If a nodes one or more requested class IDs has in its cache, it will publish on the above topic the compressed ontology chunk containing those classes. Requester node is subscribed to topic *MergeOnto*_NodeID to receive the ontology chunks and merge them.

6 SEMANTIC REASONING IN DISASTER MANAGEMENT SCENARIOS

A semantic service/resource request is a logic-based annotation expressed w.r.t. a reference ontology. The ontology URI implicitly defines the domain of the request. Semantic-based reasoning exploits the *Discovery* topic, which all semantic-enabled nodes should subscribe to. The requester starts inquiry by sending a *Discovery* message containing: (i) the reference ontology URI (ii) the topic *SemAnn*_NodeID to be used in reply messages. Nodes subscribed to *Discovery* receive the request and check whether they own services related to the same domain. In that case, they reply with compressed service annotations on *SemAnn*_NodeID. Each annotation is further associated with a service-specific topic. The requester collects all service descriptions and compares them with its request through a matchmaking process. The outcome consists in a ranked list of the services which best satisfy the request. Finally, the requester uses the topic(s) associated to the selected service(s) in order to start fruition. In case of data gathering services, such as from sensors, the requester will act as a topic subscriber to receive information; on the other hand, controllable resources require the service user to be also a publisher on the service-specific topic in order to send commands and data.

While ontology and service collection phases are based on string matching of ontology URIs and class IDs, semantic-based matchmaking for service ranking and selection exploits non-standard inferences on a KB. Consider an ontology $\mathcal{T}$ and two concept expressions *R* (the request) and *S* (a service/resource description). Standard reasoning services for matchmaking allow only to detect *full matches* and *incompatible* resources. This usually achieves poor precision and recall, because full matches are rare and incompatibility is frequent when dealing with complex descriptions. The approach adopted here exploits non-standard inference services to enable a finer matchmaking, with support for approximate matches, resource ranking based on semantic distance from the request and formal logic-based explanation of outcomes. The requester will select the available service with the highest score. A flexible semantic-based approach improves standard service discovery and allotment [12].

Particularly, in disaster management and recovery scenarios, the semantic-based reasoning could allow an advanced decision support as it can put in place novel peculiarities of information discovery and integration. Let us suppose for example a node in Data Distribution System provides sensed data referred to a particular monitored area. This information could be automatically annotated with respect to a reference ontology and it can be exploited as request to build a discovery and recovery team composed in the best possible way.

7 CONCLUSION AND FUTURE WORK

This paper presented a proposal for a novel space-based sensor network system used as disaster management through "early warning". The basic idea is to show how a metrological characterization of complex sensors could be further enhanced if provided data are annotated in a logic-based formalism and a deductive reasoning is performed on them. The resulting system should allow an improvement of performance and reliability with respect to competitor frameworks. The proposed approach is under implementation adopting a publisher/subscriber Message-Oriented Middleware named BEE-DDS as reference architecture. Preliminary tests will be devoted to assess feasibility and then measure performance.

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