Open Sensor Web Architecture: Core Services

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Abstract

As sensor network deployments begin to grow there emerges an increasing need to overcome the obstacles of connecting and sharing heterogeneous sensor resources. Common data operations and transformations exist in deployment scenarios and can be encapsulated into a layer of software services that hide the complexity of the underlying infrastructure from the application developer. NICTA Open Sensor Web Architecture (NOSA) is built upon the Sensor Web Enablement (SWE) standard defined by the Open Geospatial Consortium (OGC), which is composed of a set of specifications, including SensorML, Observation & Measurement, Sensor Collection Service, Sensor Planning Service and Web Notification Service. NOSA presents a reusable, scalable, extensible, and interoperable service oriented Sensor Web architecture that (i) conforms to the SWE standard; (ii) integrates Sensor Web with Grid Computing and (iii) provides middleware support for Sensor Webs.

Keywords

Sensor Web, Sensor Networks, Sensor Web Enablement, Service-Orientated Architecture.

1. INTRODUCTION

Sensor networks are persistent computing systems composed of large numbers of sensor nodes. Sensor nodes communicate with one another over wireless low-bandwidth links and have limited processing capacity. Sensor nodes work together to collect information about their surrounding environment, this may include things like temperature, light intensity or GPS location. As sensor networks grow and rapidly improve in their ability to measure real-time information in an accurate and reliable fashion, a new research challenge, on how to collect and analyze this generated information presents itself.

Deployment scenarios for sensor networks are countless and diverse. For example, sensors may be used for military applications, weather forecasting, tsunami detection, pollution detection, for power management in schools and office buildings. In many of these cases the software management tools for data aggregation, archiving and decision making are tightly coupled with the application scenario. However, as sensor systems grow and mature, a set of common data operations and transformations begin to emerge. For example, application scenarios will need to query to a sensor network and retrieve some resulting data. Some scenarios may require information from historic queries be stored in a repository for further analysis. Others may require regular queries to be scheduled and automatically dispatched without external operator intervention. There is a growing need to share resources among diverse network deployments to aid in tasks like decision making. For example, a tsunami warning system may rely on water level information from two geographically distributed sets of sensors developed by competing hardware vendors. This presents significant challenges in resource interoperability, fault tolerance and software reliability.

In NICTA Open Sensor Web Architecture (NOSA), we aim to implement a set of uniform operations and a standard representation for sensor data which will fulfil the software needs of a sensor network regardless of the deployment scenario. We adopt a Service Oriented Architecture (SOA) approach to describe, discover and invoke services from a heterogeneous platform using XML and SOAP standards. Services are defined for common operations including data aggregation, scheduling, resource allocation and resource discovery. Combing sensors and sensor networks with a SOA is an important step forward in presenting sensors as important resources which can be discovered, accessed and where applicable, controlled via the World Wide Web. We refer to this combination of technologies as the Sensor Web. It raises the opportunity for linking geographically distributed sensors and computational resources into a sensor-grid.

Fig. 1 demonstrates an abstract vision of the Sensor Web, various sensors and sensor nodes form a web view and are treated as available services to all the users who access the Web. A researcher wishing to predict whether a tsunami is going to occur, may query the entire Sensor Web and retrieve the response either from real-time sensors that have been registered on the web or from historical data in database. The clients are not aware of where the real sensors are and what operations they may have, although they are required to set parameters for their plan and invoke the service.

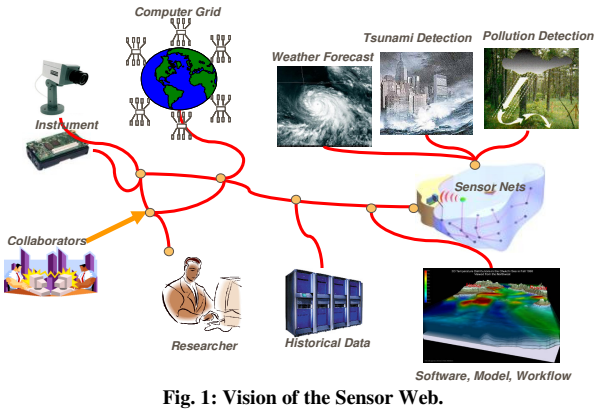


Fig. 1: Vision of the Sensor Web.

The rest of this paper is organized as follows. In Section 2, we describe the OGC Sensor Web Enablement (SWE) standards. Section 3 introduces the NOSA Architecture. Section 4 then details the design and implementation behind NOSA, including details on the core implemented services including the Sensor Collection Service (SCS), Sensor Planning Service (SPS) and Web Notification Service (WNS). Section 5 provides a detailed performance evaluation of NOSA. We give the conclusion in Section 6

2. OGC SENSOR WEB ENABLEMENT

Sensor network applications have been successfully developed and deployed around the world. Concrete examples include deployments on Great Duck Island [3], Cane-toad monitoring [4] and for Soil Moisture Monitoring [5]. However, lack of software interoperability prevents users from accessing resources generated by these applications without specialized tools. Moreover, lack of semantics to describe the sensors makes it impossible to build a uniform registry to discover and access these sensors. In addition, internal information is often tightly coupled with the specific deployment application rather than making use of standard data representations. This then restricts the ability for mining and analyzing the data for decision making.

Imagine hundreds of in-site or remote weather sensors providing real-time measurements of current wind and temperature conditions for multiple metropolitan regions. A weather forecast application may request and present the information directly to end-users or other data acquisition components. A collection of Web-based services may be involved in order to maintain a registry of available sensors and their features. Also consider that the same Web technology standard for describing the sensors, outputs, platforms, locations and control parameters is in use beyond the boundaries of regions or countries. This enables the interoperability necessary for cross-organization activities, and it provides a big opportunity in the market for customers to receive a higher quality of service. These needs drive the Open Geospatial Consortium (OGC) [1] to develop the geospatial standards that will make the "open sensor web" vision a reality [2].

In general, SWE is the standard developed by OGC that encompasses specifications for interfaces, protocols and encodings that enable discover, access, obtain sensor data as well as sensor-processing services. The following are the five primary specifications for SWE:

1. Sensor Model Language (SensorML) [7] – Information model and XML encodings that describe either a single sensor or sensor platform in regard to discovery, query and control of sensors.
2. Observation and Measurement (O&M) [14] – Information model and XML encodings for observations and measurement.
3. Sensor Collection Service (SCS) [17] – Service to fetch observations, which conform to the O&M information model, from a single sensor or a collection of sensors. It is also used to describe the sensors and sensor platforms by utilizing SensorML
4. Sensor Planning Service (SPS) [18] – Service to help users build a feasible sensor collection plan and to schedule requests for sensors and sensor platforms.
5. Web Notification Service (WNS) [19] – Service to manage client sessions and notify the client about the outcome of the requested service using various communication protocols.

As stated in [6], the purpose of SWE is to make all types of web-resident sensors, instruments and imaging devices, as

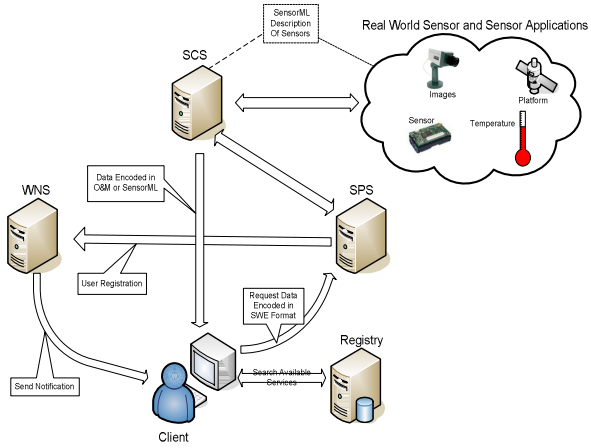


Fig. 2: A typical collaboration within Sensor Web Enablement Framework.

well as repositories of sensor data, discoverable, accessible and, where applicable, controllable via the World Wide Web. In other words, the goal is to enable the creation of Web-based sensor networks. Fig. 2 demonstrates a typical collaboration between services and data encodings of SWE.

It is important to note that NOSA is designed to interact with base stations or logical master nodes that manage collections of independent sensor nodes; thus, reducing the message passing overhead and power consumption by avoiding the direct and continuous communication with every node in each logical cluster of sensor nodes.

3. SERVICE-ORIENTED SENSOR WEB

NICTA Open Sensor Web Architecture (NOSA) is an OGC SWE standard compliant software infrastructure for providing service based access to and management of sensors. NOSA is a platform for integration of sensor networks and emerging distributed computing platforms such as SOA and Grid Computing. The integration brings several benefits to the community. The heavy load of information processing can be moved from sensor networks to the backend distributed systems such as Grids. This separation is beneficial because it reduces the energy and power needed by the sensors, allowing them to concentrate on sensing and sending information. The information processing and fusing is performed on a separate distributed system. Moreover, individual sensor networks can be linked together as services, which can be registered, discovered and accessed by different clients using a uniform protocol. Grid-based sensor applications are capable of

providing advanced services for smart-sensing by developing scenario-specific operators at runtime [8].

The various components defined for NOSA are showed in Fig. 3. Four layers have been defined, namely Fabric, Services, Development and Application. Fundamental services are provided by low-level components whereas higher-level components provide tools for creating applications and management of the lifecycle of data captured through sensor networks. NOSA provides the following sensor services:

1. Sensor notification, collection and observation;
2. Data collection, aggregation and archival;
3. Sensor co-ordination and data processing;
4. Faulty sensor data correction and management, and;
5. Sensor configuration and directory service.

Besides the core services derived from the SWE, such as the

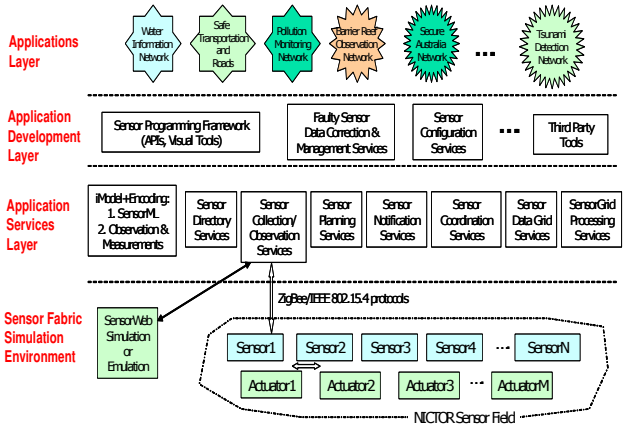


Fig. 3: High-level view of NICTA Open Sensor Web Architecture.

SCS, SPS and WNS, there are several other important services in the service layer. The Sensor Directory Service provides the capability of searching for and registering remote services and resources. The Sensor Coordination Service enables the interaction between groups of sensors, which monitor different kinds of events. The Sensor Data Grid Service publishes and maintains replicas of sensor data collected from sensor deployments. The Sensor Grid Processing Service collects the sensor data and processes it utilizing grid services. The development layer focuses on providing useful tools in order to ease and accelerate the development of sensor applications.

NOSA mainly focuses on providing an interactive development environment, an open and standards-compliant Sensor Web services middleware and a coordination language to support the development of various sensor applications. SWE only provides the principle standard of how the Sensor Web looks, but does not have any reference implementation or working system available to the community; therefore, there are many design issues to consider, including all of the common issues faced by other distributed systems such as security, multithreading, transactions, maintainability, performance, scalability and reusability, and the technical

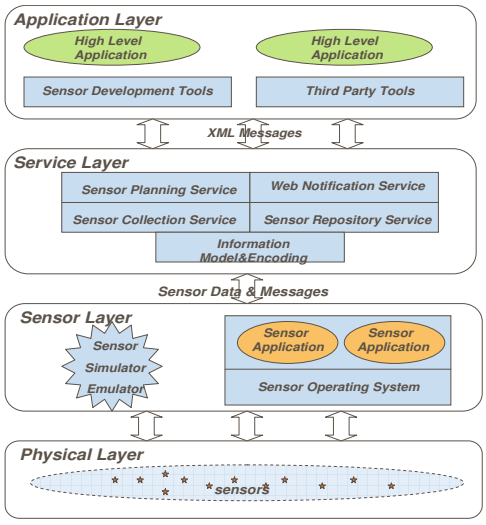


Fig. 4: A Prototype instance of NOSA.

decisions that need to be made about which alternative technologies are best suitable to the system. Fig. 4 depicts a prototype instance of NOSA, the implementation concentrates on the Service Layer and Sensor Layer as well as the XML encoding and the communication between the sensors and sensor networks. The following section will describe the key technologies that are relevant to different layers of NOSA and the design and implementation of the core services.

4. Design and Implementation

Currently, the primary design and implementation of NOSA focuses on the core services including SCS, WNS, and SPS (which extend the SWE) as well as the Sensor Repository Service (SRS) that provides a persistent data storage mechanism for the sensor and the observation data.

Fig. 5 illustrates an example of a client collection request and the invocations between relating services. As soon as the end user forwards an observation plan to the SPS, the service checks the feasibility of the plan and submits it if feasible. The user will be registered in the WNS during this process and the user id will be returned to the SPS. The SPS is responsible for creating the observation request according to user's plan and retrieving the observation and measurement (O&M) encoded data from the SCS. Once the O&M data is ready, the SPS will send an operation complete message to the WNS along with the user id and task id. The WNS will then notify the end user to collect the data via email or

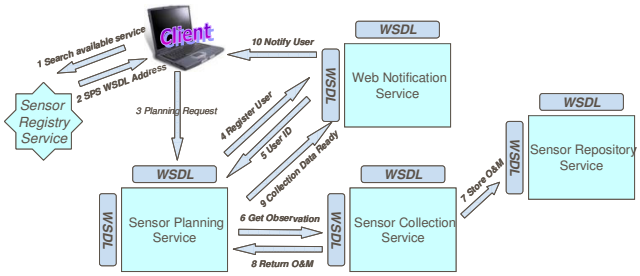


Fig. 5: A typical invocation for Sensor Web Client.

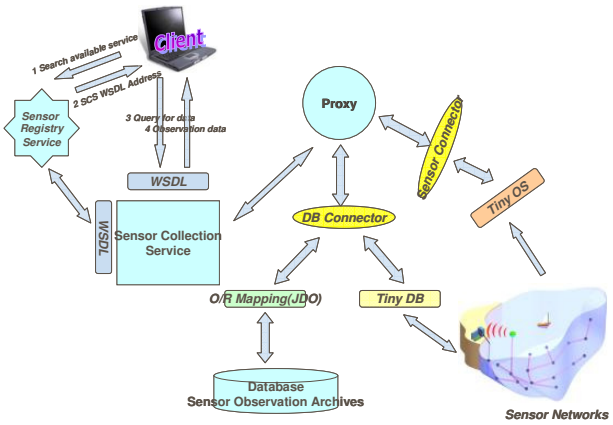


Fig. 6: Sensor Collection Service Architecture.

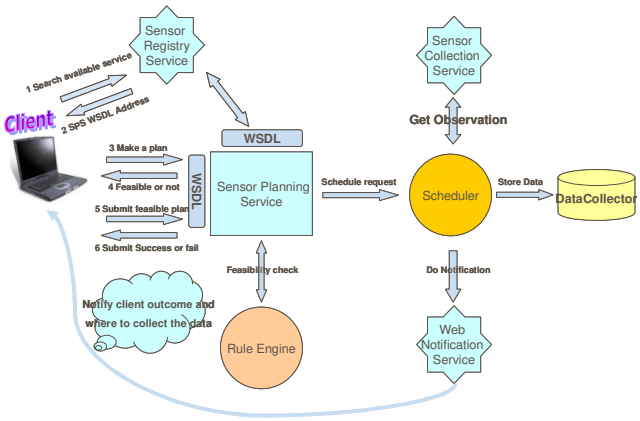


Fig. 7: Sensor Planning Service Architecture.

protocols. The following subsections describe the core set of implemented services in NOSA, namely the SCS, SPS and WNS.

A. Sensor Collection Service

The SCS is one of the most important components residing in the service layer of NOSA. The SCS is the fundamental and unique component that communicates directly with sensor networks, collects real time sensing data and then translates the resulting raw information into a XML based O&M encoding for other services to utilize and process. The SCS is the gateway for entering into the sensor networks from outside clients. The design of the SCS provides an interface to both streaming data and query-based sensor applications that are built on top of TinyOS [9] and TinyDB [10] respectively. Fig. 6 illustrates the architecture of the SCS. The service conforms to the interface definition that is described in the OGC SCS Specification and has been designed as a Web Service which connects via a proxy to either real sensors or a remote repository database. Clients need to query the Sensor Registry Service to retrieve an available SCS WSDL address. A data query request is then sent via SOAP to the SCS to obtain the resulting encoded observation data conforming to the O&M specification.

The proxy acts as an agent that works with various connectors that connect to the resources holding the information and encode the raw observation into O&M compatible data. Different types of connectors have been designed to fit into different types of resources including sensor networks running on top of TinyOS or TinyDB, and remote observation data archives. The proxy needs to process the incoming messages from the client to determine what kind of connectors, either real-time based or archive based, to use. The design of the SCS is flexible and makes it simple to extend for further development if alternative sensor operating systems are adopted by the sensor networks, such as MANTIS [11] or Contiki [12]. Except for a sensor operating system specific connector, no modifications need to be made in the current system. The design of the proxy also encourages the implementation of a cache mechanism to improve the scalability and performance of the SCS. Load balancing mechanisms can be easily added to the system as well, by simply deploying the web service to different servers.

B. Sensor Planning Service

The design of the SPS considers both the short-term and long-term requirements of the user's plan, which means that the SPS must provide response to the user immediately, rather than blocking to wait for the collection results. The SPS, shown in Fig. 7, utilizes a rule engine which reads a specific set of predefined rules in order to clarify the feasibility of the plan made by the user. The rule engine can accept rules in a configuration file as plain text, XML-based or other types of rule-based languages. Currently, the rule engine is implemented as an abstract class that can be extended by the application developers to specify a set of boundary conditions that define the feasibility of the applications. For example, in a simple temperature application, a boundary condition for the temperature may be a range from 0 to 100.

The most important component that makes the SPS suitable for short or long term plan execution is the Scheduler which is implemented as a separate thread running in the background. The execution sequence of the Scheduler is the following; (i) the scheduler composes a collection request according to user's plan and then invokes the getObservation method on the SCS, (ii) the scheduler then asks the DataCollector to store the resulting observation data for users to collect afterward, and (iii) sends notification to the WNS indicating the outcome of the collection request. The time of the execution in the scheduler varies based on the requirements of the user's plan. The client receives a response indicating that the plan will be processed right after the plan is submitted to the SPS. The scheduler deals with the remaining time consuming activities. The client may get the notification from the WNS as soon as the WNS receives a message from the scheduler, the client can then collect results from the DataCollector.

C. Web Notification Service

The current design of WNS is shown in Fig. 8, which contains two basic components: AccountManager and Notification. The SPS may request to register users via WNS, which asks the AccountManager to manage the user account in the DBMS in order to retrieve user information in the

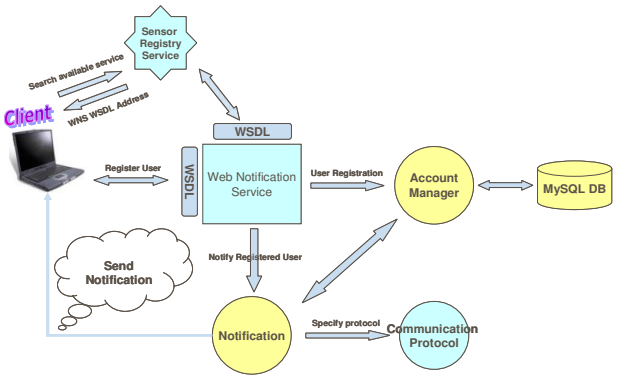


Fig. 8: Web Notification Service Architecture.

subsequent operations. The Notification is used to create a specific communication protocol and send the messages via the protocol to the user that has been registered in the DBMS. Currently, an email protocol has been implemented to send messages via email. Further implementations can be easily plugged into the existing architecture by implementing the CommunicationProtocol interface.

5. EVALUATION

The experiment platform for the services was built on TOSSIM [15], a discrete event simulator that can simulate thousands of motes running complete sensor applications and allow a wide range of experimentation, and Crossbow's MOTE-KIT4x0 MICA2 Basic Kit [16] which consists of 3 Mica2 Radio boards, 2 MTS300 Sensor Boards, a MIB510 programming and serial interface board. The experiment concentrated on the SCS, since it is the gateway for other services to sensors, which would be the most heavily loaded service and possible bottleneck for the entire system.

Fig. 9 illustrates the SCS deployed on Apache Tomcat 5.0 server running on two different machines, one of which is hosting the TinyDB application under TOSSIM and the other

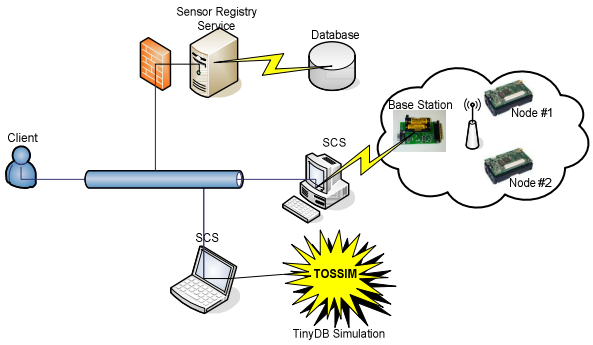


Fig. 9: Deployment of Experiment.

the Temperature Monitoring application under Crossbow's motes. A Sensor Registry Service is also configured on a separate machine that provides the functionality to access the sensor registry and data repository. A simple temperature monitoring application has been developed. The application is programmed using nesC [13] and uses simple logic, which broadcasts the sensing temperature, light and node address to

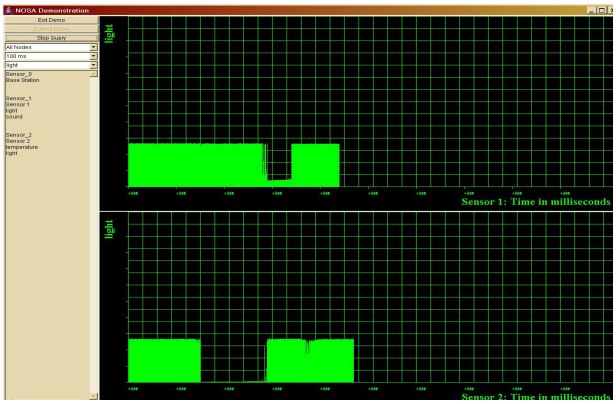


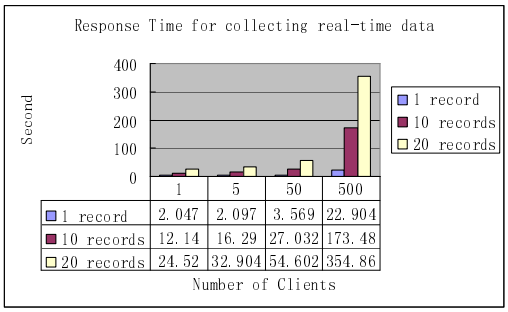
Fig. 10: Client showing visualization of results received from temperature monitoring application called from SCS.

the sensor network at regular intervals. The simple application does not consider any multi-hop routing or energy saving mechanisms. Before installing the application on the Crossbow motes, the functionality is verified under the TOSSIM simulator. Once the application has been successfully installed onto each mote via the programming board, a wireless sensor network is setup using the two nodes and one base station connecting to the host machine via serial cable. Fig. 10 displays the results retrieved by a client from the SCS interfaced with the temperature monitoring application. The light intensity level is illustrated by the graph plot; two individual sensors each take recordings at 100ms intervals. Recordings from sensor one are illustrated in the top half of the window and sensor two on the bottom half. A change in the graph plot indicates a variance in the incoming light intensity for each sensor. The left-hand-side column contains SensorML descriptions of the sensors retrieved by the client from the SCS.

Regarding scalability, a simulation program that can stimulate different numbers of clients running at the same time has been used exclusively for the SCS. The performance measured by time variable (per second) for both auto-sending and query-based applications running on top of TinyOS is shown in Fig. 11 and Fig. 12. Fig. 11 presents that the result of the auto-sending mode application is moderate when the number of clients who request the observation simultaneity is small. Even when the number of clients reaches 500, the response time for a small number of records is also acceptable. In contrast, the result shown in Fig. 12 is fairly unacceptable as even just one client requesting a single observation takes 34 seconds. The response time increases near linearly when the number of clients and the number of records goes up. The reason why the query-based approach has very poor performance is due to the execution mechanism of TinyDB. A lot of time is spent on initializing each mote, and the application can only execute one query at a time, which means another query needs to wait until the current query is either completed or terminated. A solution to this problem may require the TinyDB application to run a generic query for all clients, whereas a more specific query can be executed in-memory according to the observation data collected from the generic query. There are several possible ways to enhance the

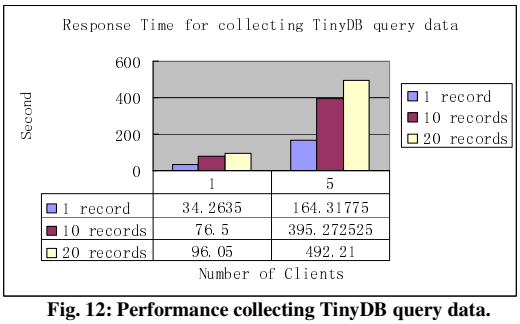
performance. A caching mechanism may be one of the possible approaches, the recent collected observation data can be cached in the proxy for a given period of time and the clients who request the same set of observation data can be read the observation data from the cache.

However, as the data should be kept as close to real time as possible, it is quite difficult to determine the period of time for the cache to be valid. A decision can be made according to the dynamic features of the information that the application is



	1	5	50	500
1 record	2.047	2.097	3.569	22.904
10 records	12.14	16.29	27.032	173.48
20 records	24.52	32.904	54.602	354.86

Fig. 11: Performance collecting auto-sending data.



	1	5
1 record	34.2635	164.31775
10 records	76.5	395.272525
20 records	96.05	492.21

Fig. 12: Performance collecting TinyDB query data.

targeting. For example, the temperature for a specific area may not change dynamically in minutes or hours. Consequently, the period of time setting for the cache for each sensor application can vary based on the information the sensor is targeting. Enhancement of query performance can be achieved by utilizing query mechanism such as XQuery of the XML data directly other than asking the real sensor itself executing the query similar to TinyDB.

6. CONCLUSION

NOSA is an implementation of the OGC SWE standard, which standardizes the vision of Sensor Web. SensorML, O&M, SCS, SPS and WNS are coupled together to create an integrated platform for registering, discovering and accessing heterogeneous distributed sensors using Web Services. We have introduced the design and implementation of the core services in NOSA. In future work we aim to extend NOSA beyond the SWE and provide additional services for processing information collected from sensor resources accompanied by computational grids. We have detailed the scalability and performance of the prototype SCS which forms the backbone of the core services. Future works include implementing all methods described in the specifications of SWE services that are not currently available, a caching mechanism for the SCS and extensions of notification protocols for the WNS.

ACKNOWLEDGEMENT

We thank Jiye Lin for his contribution towards the development of SensorWeb repository. We thank all members of the NOSA project especially those involved in advancing SensorWeb into the future. Special thanks to Ingebjorg Theiss for her contribution of the client GUI snapshot (GUI code presented in Fig. 10). Bohdan Durnota was a visiting researcher for GRIDS Lab during 2005 and offered guidance during the project formulation and prototype development.

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