Proceedings of Australasian Conference on Robotics and Automation, 2-4 Dec 2013, University of New South Wales, Sydney Australia

Sustainability, Scalability, and Sensor Discovery with Cloud Robotics

Claire D'Este[1], Chris Sharman[1], Ritaban Dutta[1], Ahsan Morshed[1], Jessica Lethbridge[2], Andrew Terhorst[1], and Ben Howell[1]
[1]CSIRO Computational Informatics, Hobart, TAS Australia
[2]University of Tasmania, Hobart, TAS Australia
claire.deste@csiro.au

Abstract

Ongoing robotic systems are primarily undertaken by large organisations and are closed systems. We describe an extension to the cloud robotics concept that encourages reuse of sensor data collected from robots and sensor networks, and eases the economic and technical burden on small industry and government organisations. This paper describes the innovations currently in development by CSIRO that contribute to improved sustainability, scalability and sensor discovery in robotics using a cloud based data management system. Sensor Web and Linked Open Data principles are implemented to provide standardised interfaces to data sharing and robot tasking.

1 Introduction

Robot data, like other sensor data is, is generally "locked inside specific applications and only accessible within organisational boundaries" [Le-Phuoc and Hauswirth, 2009]. Closed robotic systems place the technical and financial burden on a single organisation, or project. The majority of robot projects are still performed in an adhoc fashion and last the length of a funding grant. This is a wasted opportunity for enhancing autonomous decision making in the robot with external data, or for providing potentially useful data to other systems.

The *Sense-T* project aims to provide economic, social and environmental benefit to Tasmania by providing access to standard interfaces and analyses that encourage reuse of new and existing sensor data sources. This approach also aims to improve the sustainability of individual monitoring projects. The applications of particular focus are agriculture, aquaculture [D'Este *et al.*, 2012], water resource management, and food logistics.

The sensor data sources in use currently by *Sense-T* projects are static sensing nodes, or data sets of historical manual sampling. However, many observable systems of interest are highly localised, such as pasture growth monitoring, and purchasing and maintaining an extensive sensor network can be prohibitively expensive. Mobile sensor sources open up opportunities for sensing at higher spatial resolutions with potentially much lower technical overhead and hardware cost.

One initiative of *Sense-T* is in developing an interoperable framework based on Linked Open Data [Berners-Lee, 2013] and Sensor Web [Liang and Tao, 2005] principles called the *SensorCloud*. Applying this same approach to robot data significantly extends the concept of "cloud robotics", which to date has been limited to off-board processing, off-board storage, and the downloading of behaviours [Guizzo, 2011] [Hu *et al.*, 2012]. Robots can then use the observations of other robots and static sensor nodes in their autonomous decision making, and provide their own data for the reuse of others.

Although many organisations publish their sensor data publically available on the web, one of the currently missing components is a service that allow autonomous discovery of appropriate sensor data sources. We achieve this with Linked Open Data principles [Berners-Lee, 2013] applied to robot data.

This paper describes the innovations currently in development by CSIRO that contribute to improved sustainability, scalability and sensor discovery in robotics using a cloud based data management system.

2 Related Work

Networked robotics has been around since the 1980s. Initial research focussed on networking multiple robots for cooperation [Parker, 2000] and with the rise of the internet this has evolved to encompass communication with the wider world. [Mezei *et al.*, 2012] discuss task assignment and event handling for a network of robots working within a network of static sensors.

[Wang *et al.*, 2012] studied the issues involved in multisensor data retrieval in cloud robotics systems. They identified four main characteristics of data retrieval, time of response, reliability of response, data compatibility and data re-computation. They also identified three issues, synchronisation of data, efficiency of resource retrieval and data fusion. They used a Twisted based network to build a framework for data retrieval.

[Quintas *et al.*, 2011] envisioned a system where the cloud could be used to allow robots to access and learn new programming and to allow the transfer of context belonging to a person between robotics systems caring for them to maximise the effectiveness of their care.

[Chen *et al.*, 2010] developed a Robot-As-A-Service (RaaS) approach to discovery and publishing of services, direct access to application (combinations of services) and functionality performance for robots used in classrooms.

[Waibel *et al.*, 2011] developed a system called RoboEarth, which works to build a system that provides a structured interpretation of the world by gathering information from robots using Linked Open Data and Semantic Web principles. However, the data sources used were from their own closed system.

[Suri *et al.*, 2007] used intelligent agents to coordinate and distribute goals and tasks within the Sensor Web. Their Sensor Web consisted of in-situ robots and remote sensing satellites. The Science Agents existing within the web were assigned goals and event triggers that allow them to achieve their goals in the correct contexts.

Juarez has developed Semantic Web compatible robot descriptions to fill the interoperability gap between virtual worlds and robots [Juarez, 2012].

3 The SensorCloud

Advances in sensor technology and distributed computing, coupled with the development of open standards that facilitate sensor/sensor network interoperability, are contributing to the emergence of the 'Sensor Web'[Liang and Tao, 2005]. The Sensor Web can be described as an advanced Spatial Data Infrastructure (SDI) for [near] real-time situation awareness. Sensor Web enablement currently provides much of the necessary functionality to achieve utilisation of sensor data from external sources.

Sensor Web Enablement (SWE) is an Open Geospatial Consortium (OGC) initiative that extends the OGC open web services framework [Botts, 2011] by providing additional services and encodings for integrating web-connected sensors and sensor systems. SWE services are designed to enable *discovery* of sensor assets and capabilities, *access* to these resources through data retrieval and subscription to alerts, and *tasking* of sensors to control observations [Botts, 2011]. SWE enables interoperability between heterogeneous sensors, simulation models and decision support systems.

Sensor web enabled systems have been used to exchange sensor data and increase autonomy in a distributed set of sensing devices on land, water and air [Underbrink *et al.*, 2011]. However, these use data from within one project rather than attempting to use whatever relevant data could be found. Projects such as GeoCens [Liang and Huang, 2013] may provide a search engine for sensor observations; crawling the web for sensor web enabled data sources.

A key aspect of the *Sense-T* project is the continued development of the *SensorCloud* architecture, which is an implementation of the Sensor Web concept with a low barrier to entry. Complete OGC Sensor Web implementations are rare due to the high complexity involved. The *SensorCloud* provides a RESTful API (REpresentational State Transfer - Application Programming Interface), which encourages scalability and generality.

Sensor Web applications are generally based on SensorML (Sensor Markup Language), which is designed to be very flexible so that it can be easily applied in a variety mission planning applications. Unfortunately, this flexibility comes at a price of true interoperability, which requires stronger enforcement of encoding rules and well-defined semantics. Though the W3C Semantic Sensor Network Incubator Group (SSN-XG) have developed a sensor ontology that can be used for semantic mark-up of SensorML documents [Barnaghi *et al.*, 2011], SensorML is not grounded enough for sensor discovery [Simonis *et al.*, 2011].

The CSIRO is promoting the development of a new sensor mark-up language (dubbed Starfish Fungus Language or *FL). *FL is used to describe sensor properties, capabilities, and corresponding deployment aspects. Furthermore, *FL features a clear separation between the physical device (Sensor), its model specific composition (SensorCharacteristics), and the specific procedures running on a physical device or subcomponents respectively (SensingProcedure). By this, it follows its main conceptual ancestor, the sensor ontology developed by the W3C Semantic Sensor Network Incubator Group [Barnaghi *et al.*, 2011]. The relative simplicity and structure of *FL, as well as its close alignment with O&M, make *FL better suited for sensor discovery.

SensorCloud service will return *FL sensor descriptions encoded in either Extensible Markup Language (XML), JavaScript Object Notation (JSON) or Resource Description Framework (RDF). The RDF encoding will allow linking of sensor descriptions with associated observation archives and other digital information (and vice versa). The service is being designed to enable discovery of sensors and observations fit-for purpose. A key enabling technology is Linked Open Data.

3.1 Linked Open Data

Linked Open Data is [Bizer *et al.*, 2008]:

> "about employing the Resource Description Framework (RDF) and the Hypertext Trans-

fer Protocol (HTTP) to publish structured data on the Web and to connect data between different data sources, effectively allowing data in one data source to be linked to data in another data source."

Berners-Lee [Berners-Lee, 2013] outlines four design principles for LOD:

1. Name using Uniform Resource Identifiers (URIs)
2. Link the names with HTTP URIs
3. At the link destination provide standardised and useful information, such as RDF
4. Link to other URIs to encourage further discovery

The benefit for extending the cloud robotics concept with LOD principles and standards is chiefly in how it provides a global namespace and a platform for the discovery of sensor data sources. Robots can become the users or sources in a 'sensor data mashup' [Le-Phuoc and Hauswirth, 2009].

3.2 Scalability

The *Sensor Messaging Gateway* (SMG) [Hugo *et al.*, 2011] provides a modular plug-in type system allowing sensor sources, pre-processors and listeners to be easily added to the system and enabled or disabled using basic configuration files. The SMG can act as a stand alone system, a publisher, a subscriber, and both a publisher and subscriber (i.e. a message broker). Using a publisher/subscriber configuration allows the *SensorCloud* to be distributed and scalable in order to cope with a multitude of sensors and sensor network data sources together with numerous distribution channels with the added benefit of data and network redundancy if desired. The publish/subscribe architecture provides a flexible system allowing sensor feed subscription on a granular level, thus, consumers need only subscribe to the sensors they are interested in.

Further scalability can be gained as multiple sensor sources can stream to a single SMG instance, or SMG instances can be created on demand. MongoDB is a scalable document oriented database system used in the *SensorCloud* system to store historical sensor data. MongoDB instances can also be sharded and replicated as required.

4 SensorCloud Robotics

The following sections describe our approaches for extending the *SensorCloud* to include robotic systems, Figure 1.

We make use of the Robot Operating System (ROS) initiative, which has significant uptake across robot platforms. ROS attempts to reduce the technical burden of developing robot systems by provided a standard messaging system as well as the sharing of commonly required functionality, such as navigation and visualisation.

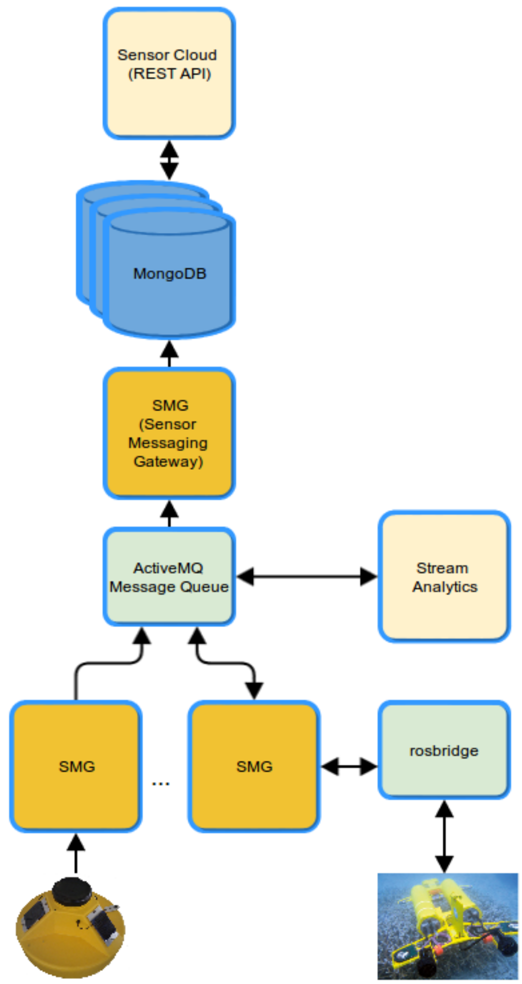

Figure 1: Scalability and the SensorCloud Robot

4.1 Data Representation

We make use of a package that exposes ROS topics called rosbridge [Mace, 2013]. This allows us to create a sensor data stream from sensor, or engineering, data that any ROS node is publishing.

The following is the current approach to sensor stream URIs in the *SensorCloud*. This URI scheme is used to refer to the data stream of a sensor. These URIs must resolve to dynamically generated documents describing the data stream and further links to other systems providing additional data services.

```
<url>/<sourceid>/stream/platform/<platform>
  /sensor/<sensor>/phenomenon/<phenomenon>
```

The local ROS topics are mapped onto persistent URIs, in the SensorCloud a 'sensor' can be anything producing a time series data stream, which could include derived products such as location. For our robots we map ROS stack, node, and topic names to the platform, sensor and stream. The URL is that which is used to expose the topics via rosbridge.

```
<url>/<sourceid>/stream/platform/
  <ROSstack>/sensor/<ROSnode>
  /phenomenon/<ROStopic>
```

The following example is from the sea water temperature sensor on our autonomous surface vehicle, Straycat.

```
http://www.sense-t.csiro.au/id/stream/
  platform/straycat/sensor/raymarine/
  phenomenon/sea_water_temperature
```

When the sensor is mobile this requires additional information so we can identify exactly where an observation was made. We require an association to be made between the localising sensor data stream (typically GPS in our applications) and any other sensing streams that were recorded during the deployment. This is achieved within the *FL representations of the platform deployment. Location data is treated the same as any other observational data except that once linked to a platform location it will be spatially indexed to allow for efficient platform discovery queries.

A *FL a static sensor node has often only a single instance of `PlatformDeployment` as the platform stays in the same place for the entire deployment. The `deploymentLocation` refers to a single location and the `operationArea` bounding box is very limited. The differences in representation can be seen in Figure 2.

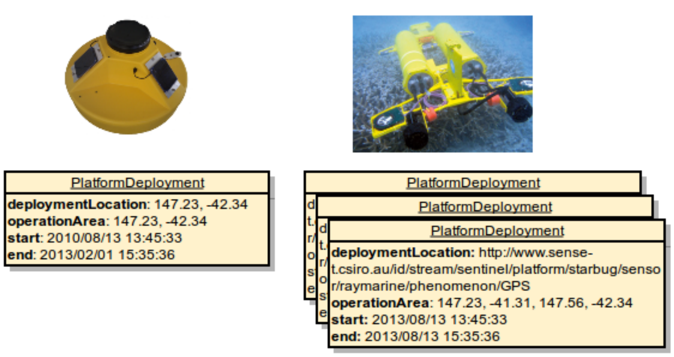

Figure 2: *FL PlatformDeployment representations for static and mobile sensing.

4.2 Sensor Discovery

Referring to a sensor data stream via a URI provides a persistent global identifier that can be used directly for variables within applications. This allows the applications to autonomously discover and use data sources based on the specified context. In the case of *SensorCloud* robots the sensor data it provides can be discovered by others, such as decision support systems, or it can use sensor data from other sensors and robots in its autonomous decision making.

The *SensorCloud* REST API provides the ability to query for sensor data sources spatially, temporally, and by phenomena.

Some example queries include:

- What are the available sources in Hobart?
- What are the available sources who have observations for today?
- What are the available sources for wind direction?

Below is a sample query for sources available in a radius around a point:

```
http://sense-t.csiro.au/sensorcloud/v1/
  platformDeployment?spatialFilter=
  radius(147.579,-41.575,10000000)
```

These conditions can also be combined to search for specific areas over specific times for specific phenomenon.

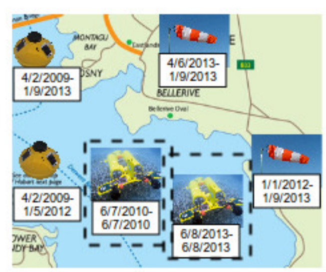

Figure 3: Example of available data sources in a geographical area with different deployment times.

Figure 3 shows example sensor sources for a geographical area. Different sources would be returned depending on the temporal and spatial bounds of the query. If we asked for only wind direction observations then only the weather station sources would be provided.

We are currently investigating how sensor sources might be automatically created in the *SensorCloud* from the search results of GeoCENS [Liang and Huang, 2013].

Information on the sensing platform is provided so the ingester can judge if the source is fit for purpose; including calibration information. In future work this will include quantifying the uncertainty of the data stream. In previous work we have developed methods for automated quality assessment for marine sensing [Smith *et al.*, 2012], but this must be extended for other sensing; including mobile. The ingester may also desire to filter based on the reliability of the sensor source, which we have demonstrated for a water management sensor network [Dutta *et al.*, 2013].

The API returns a list of URIs which become topic names available via rosbridge. Nodes on the robot can then subscribe to these topics and they can be used as any other sensor data provided by the robot's own sensors.

4.3 Analysis

Once the robot has access to many Linked Open Data sources it can then include them in its own autonomous decision making. Data from a variety of platforms can be injested, analysed and used to determine action. We have performed preliminary experiments with an autonomous surface vessel that uses publically accessible sensor data sources to determine if poor quality data from a static sensor node is due to equipment fault or an actual environmental event [D'Este *et al.*, 2011].

An extension to this work is in progress that uses external sensing sources via the *SensorCloud* to determine cost-risk-benefit factors for path planning. For example, additional cost is attributed to potential locations that require driving a marine vehicle directly into strong wind.

Making an optimal and cost effective strategy to conduct a data capturing experiment using a robotic sensory node in a real world environment could be very challenging due to difficult geographical location of the sensor node or sensor station, extreme environmental conditions, communication network failure, and technical failure of the robotic node. To address this, there is a need for on demand complementary knowledge integration from multiple data sources and automatic interpretation of the knowledge. To achieve this we have developed a cloud based Intelligent Environmental Knowledgebase (*i-EKbase*) system [Morshed and Dutta, 2013] which is developed using Linked Open Data principles, Semantic Knowledge Integration and Machine Learning Analytics for better knowledge integration and autonomous knowledge intervention on the web.

The main focus of the *i-EKbase* is to provide in-depth historical environmental context regarding a location of interest to a cloud robotics platform capturing high spatial resolution data. Already integrated heterogeneous data sources include Bureau of Meteorology-Long Paddock SILO [DSITIA, 2013], Australian Water Availability Project (AWAP) [CSIRO, 2013b], Australian Soil Resource Information System (ASRIS) [CSIRO, 2013a], Australian Cosmic Ray Soil Moisture Sensor Network (CosmOz) [CSIRO, 2013c], NASAs LandSAT satellite imagery of continental earth surfaces databases [NASA, 2013], and Australian Digital Elevation (DED) databases [Geoscience Australia, 2013]. This system would be used to complement the real time sensor and sensor network data stream for better decision support.

This research study proposes to use the *i-EKbase* system [Morshed and Dutta, 2013] in conjunction with *SensorCloud* to guide the robotic platform to capture "fit for purpose" environmental data..

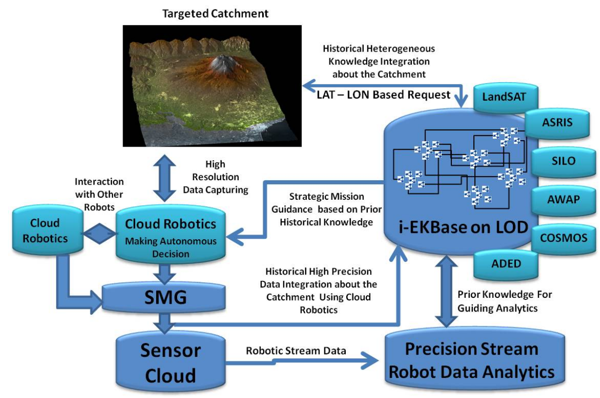

Figure 4: Architectural integration and workflow between i-EKbase system and Cloud Robotics via the *SensorCloud*.

4.4 Tasking

Figures 1 and 4 show bidirectional communications between the sensor stream analytics and the robot. Our use cases require the functionality in the robot to respond to environmental events.

We have implemented interfaces inspired by the OGC's Sensor Planning Service (SPS) [OGC, 2013]:

- GetCapabilities - a list of possible tasks
- GetFeasability - can the task be completed given the current status?
- DescribeTasking - more information on specific tasks
- Submit/Update/Cancel/GetStatus
- DescribeResultAccess - how to retrieve the results of a task

For decades domain specific languages have been created for robotics to allow standardised tasking methods. Implementing it in a Semantic Web compatible standard allows the use of current querying technologies such as the RDF query language SPARQL. We can then search the available robots for those with specific capabilities.

This study also aims to expand the agricultural sustainability to precision agriculture using high resolution Linked Open Robot Data (LORD) [D'Este *et al.*, 2013] based on the *SensorCloud*. An agricultural mobile sensing cloud robotics platform would be deployed as a high resolution distributed data capturing and processing service made available to decision support systems. A cloud robotics platform guided by the LOD ontology might discover data from the *i-EKbase* system and combine it with its own sensor data for precision agricultural decision support. This research aspect is also aiming for *behavioural cloning* [D'Este *et al.*, 2003] research for capturing the manual data gathering and agricultural decision making processes to be incorporated into the automated LORD tasks.

The Robotic RDF database for cloud robotics is still in development, however, we have designed a conceptual model for robot data using standard vocabularies (i.e., SKOS [W3C Semantic Web, 2013], RDF, Geo etc.) from W3C standards. All the data is stored in a triplestore called Sesame [Aduna, 2013], which is integral part of *i-EKbase* and data can be queried by using the SPARQL-a query language for RDF. Figure 5 shows an example of the Robotic RDF in development.

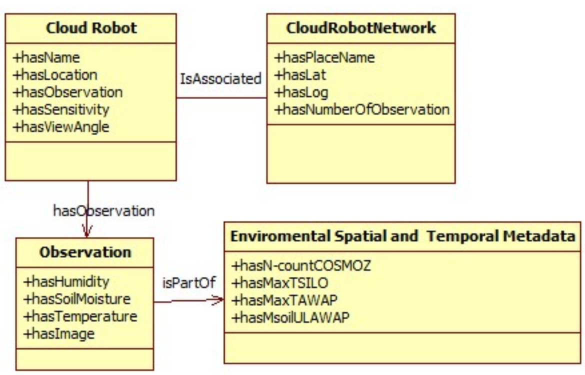

Figure 5: An example of the Robotic RDF in development.

An RDF capability description is below based on [Juarez, 2012]:

```
Class:  CanDive
  subClassOf:  Queries
  EquivalentTo :  hasCapability some
    DivingCapability

Class:  DivingCapability
  subClassOf:  Capability
  EquivalentTo :  hasInput some StringInput,
    requires some BuoyancyChange or some
    Thrusters, requires some Waterproofing
```

A SPARQL query may then find only the robots that can dive under water:

```
SELECT ?robot
  FROM <robotontology.rdf>
  WHERE {
    ?robot rdf:type rdb:CanDive.
    }
```

5 Conclusion

Sustainability and scalability is an ongoing challenge for robotics. A real-time interoperable framework creates opportunity for reuse of robot data, which in turn reduces the technical and economic burden on small organisations. Cloud computing practices, which create resources on demand, create a platform on which this approach can scale to a statewide level, and potentially beyond. The integration with ROS opens up the system to a wide range of robot platforms. The integration with *i-EKBase* extends the impact of observations collected via robot.

We have presented CSIRO's *SensorCloud* approach to these issues and how they contribute to the goals of *Sense-T*, however, there are benefits to be gained by any isolated robotic system by applying Linked Open Data and Sensor Web [Liang and Tao, 2005] principles, and cloud computing practices.

Acknowledgments

The CSIRO Intelligent Sensing and Systems Laboratory and the Tasmanian node of the Australian Centre for Broadband Innovation is assisted by a grant from the Tasmanian Government which is administered by the Tasmanian Department of Economic Development, Tourism and the Arts. The *SensorCloud* architecture includes additional intellectual contribution from David Biggins, Daniel Hugo, Doug Palmer, Chris Peters, and Peter Taylor.

References

[Aduna, 2013] Aduna. Sesame triple store. http://www.openrdf.org, 2013.

[Barnaghi *et al.*, 2011] Payam Barnaghi, Michael Compton, Oscar Corcho, Ral Garca Castro, John Graybeal, Arthur Herzog, Krzysztof Janowicz, Holger Neuhaus, Andriy Nikolov, and Kevin Page. Semantic Sensor Network XG Final Report. Technical report, World-Wide Web Consortium, June 2011.

[Berners-Lee, 2013] Tim Berners-Lee. Linked data design issues. http://www.w3.org/DesignIssues/LinkedData.html, 2013.

[Bizer *et al.*, 2008] Christian Bizer, Tom Heath, Kingsley Idehen, and Tim Berners-Lee. Linked data on the web (ldow2008). In *Proceedings of the 17th international conference on World Wide Web*, pages 1265–1266. ACM, 2008.

[Botts, 2011] Mike Botts. Sensor web enablement intro and v2.0 directions. http://q2o.whoi.edu/files/SWE_Intro_and_Status_2010.pdf, May 30 2011.

[Chen *et al.*, 2010] Yinong Chen, Zhihui Du, and Marcos García-Acosta. Robot as a service in cloud computing. In *Service Oriented System Engineering (SOSE), 2010 Fifth IEEE International Symposium on*, pages 151–158. IEEE, 2010.

[CSIRO, 2013a] CSIRO. Australian soil resource information system (ASRIS) data source. http://www.asris.csiro.au, 2013.

[CSIRO, 2013b] CSIRO. Australian water availability project (AWAP) data source. http://www.eoc.csiro.au/awap, 2013.

[CSIRO, 2013c] CSIRO. Cosmoz: Australian national cosmic ray soil moisture monitoring facility data source. http://www.ermt.csiro.au/html/cosmoz.html, 2013.

[D'Este *et al.*, 2003] Claire D'Este, Mark O'Sullivan, and Nicholas Hannah. Behavioural cloning and robot control. In *Robotics and Applications*, pages 179–182, 2003.

[D'Este *et al.*, 2011] Claire D'Este, Andrew Terhorst, Greg Timms, John McCulloch, and Chris Sharman. Adaptive marine monitoring via the sensor web. In *IEEE Conference on Intelligent Robots and Systems: Workshop on Robotics for Environmental Monitoring*, San Francisco, USA, 2011.

[D'Este *et al.*, 2012] Claire D'Este, Ashfaqur Rahman, and Alison Turnbull. Predicting shellfish farm closures with class balancing methods. In Michael Thielscher and Dongmo Zhang, editors, *AI 2012: Advances in Artificial Intelligence*, Lecture Notes in Computer Science, pages 39–48. Springer Berlin Heidelberg, 2012.

[D'Este *et al.*, 2013] Claire D'Este, Ritaban Dutta, and Ahsan Morshed. Linked open robot data. In *Workshop on Semantic Machine Learning and Linked Open Data, International Semantic Web Conference*, 2013.

[DSITIA, 2013] Queensland State Department of Science, Information Technology, Innovation and the Arts DSITIA. Silo data source. http://www.longpaddock.qld.gov.au/silo, 2013.

[Dutta *et al.*, 2013] Ritaban Dutta, Claire DEste, and Ahsan Morshed. Dynamic evaluation and visualisation of the quality and availability of sensor data sources. *International Journal of Advanced Computer Science and Applications*, 2013.

[Geoscience Australia, 2013] Geoscience Australia. Australian digital elevation database (ded). http://www.ga.gov.au/topographic-mapping/digital-elevation-data.html, 2013.

[Guizzo, 2011] Erico Guizzo. Robots with their heads in the clouds. *Spectrum, IEEE*, 48(3):16–18, 2011.

[Hu *et al.*, 2012] Guoqiang. Hu, Wee Peng Tay, and Yonggang Wen. Cloud robotics: architecture, challenges and applications. *Network, IEEE*, 26(3):21–28, 2012.

[Hugo *et al.*, 2011] Daniel Hugo, Ben Howell, Claire D'Este, Greg Timms, Chris Sharman, Paulo De Souza, and Simon Allen. Low-cost marine monitoring: from sensors to information delivery. In *OCEANS 2011*, pages 1–7. IEEE, 2011.

[Juarez, 2012] Alex Juarez. *Semantic Web for Robots: Applying Semantic Web technologies for interoperability between virtual worlds and real robots*. PhD thesis, Proefontwerp Technische Universiteit Eindhoven, 2012.

[Le-Phuoc and Hauswirth, 2009] Danh Le-Phuoc and Manfred Hauswirth. Linked open data in sensor data mashups. In *Proceedings of the Conference on Semantic Sensor Networks*, 2009.

[Liang and Huang, 2013] Steve HL Liang and Chih-Yuan Huang. GeoCENS: A geospatial cyberinfrastructure for the world-wide sensor web. *Sensors*, 13(10):13402–13424, 2013.

[Liang and Tao, 2005] Croitoru Arie Liang, Steve and Vincent Tao. A Distributed Geospatial Infrastructure for the Sensor Web. *Computers & Geosciences*, 31(2):221–231, 2005.

[Mace, 2013] J. Mace. Rosbridge suite. http://www.ros.org/wiki/rosbridge_suite, 2013.

[Mezei *et al.*, 2012] I Mezei, V Malbasa, and I Stojmenovic. Task assignment in wireless sensor and robot networks. *Telecommunications Forum (TELFOR), 2012 20th*, pages 596–602, 2012.

[Morshed and Dutta, 2013] Ahsan Morshed and Aryal J. Dutta, Ritaban. Recommending environmental knowledge as linked open data cloud using semantic machine learning. In *29th IEEE International Conference on Data Engineering*, pages 27–28, 2013.

[NASA, 2013] National Aeronautics and Space Administration NASA. Landsat. http://landsat.usgs.gov, 2013.

[OGC, 2013] Open Geospatial Consortium OGC. Sensor planning service (SPS). http://www.opengeospatial.org/standards/sps, 2013.

[Parker, 2000] Lynne E Parker. Current State of the Art in Distributed Autonomous Mobile Robotics. In *Distributed Autonomous Robotic Systems 4*, pages 3–12. Springer Japan, Tokyo, 2000.

[Quintas *et al.*, 2011] Joao Manuel Quintas, Paulo Jorge Menezes, and Jorge Manuel Dias. Cloud robotics: Towards context aware robotic networks. *Proc. Robo*, 2011:420–427, 2011.

[Simonis *et al.*, 2011] Ingo Simonis, Christian Malewski, Andrew Terhorst, Peter Taylor, and Simon Cox. *FL Starfish Fungus Language for Sensor Description. Technical report, Open Geospatial Consortium, 2011.

[Smith *et al.*, 2012] Daniel Smith, Greg Timms, Paulo De Souza, and Claire DEste. A bayesian framework for the automated online assessment of sensor data quality. *Sensors*, 12(7):9476–9501, 2012.

[Suri *et al.*, 2007] Dipa Suri, Adam S Howell, Douglas C Schmidt, Gautam P Biswas, John S Kinnebrew, William R Otte, and Nishanth Shankaran. A Multi-Agent Architecture Provides Smart Sensing for the NASA Sensor Web. In *Aerospace Conference, 2007 IEEE*, pages 1–9, 2007.

[Underbrink *et al.*, 2011] Al Underbrink, Andrew Potter, Ken Witt, and Jason Stanley. Modeling sensor web autonomy. In *Aerospace Conference, 2011 IEEE*, pages 1 –14, march 2011.

[W3C Semantic Web, 2013] W3C Semantic Web. Simple knowledge organization system. http://www.w3.org/2004/02/skos, 2013.

[Waibel *et al.*, 2011] Markus Waibel, Michael Beetz, Javier Civera, Raffaello D'Andrea, Jos Elfring, Dorian Glvez-Lopez, Kai Haussermann, Rob Janssen, J.M.M. Montiel, Alexander Perzylo, Bjorn Schiessle, Moritz Tenorth, Oliver Zweigle, and Rene and van de Molengraft. Roboearth. *Robotics Automation Magazine, IEEE*, 18(2):69 –82, june 2011.

[Wang *et al.*, 2012] Lujia Wang, Ming Liu, M Q H Meng, and R Siegwart. Towards real-time multi-sensor information retrieval in Cloud Robotic System. In *Multisensor Fusion and Integration for Intelligent Systems (MFI), 2012 IEEE Conference on*, pages 21–26, 2012.