Processing online crop disease warning information via sensor networks using ISA ontologies

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Abstract: Growing demand for food is driving the need for higher crop yields globally. Correctly anticipating the onset of damaging crop diseases is essential to achieve this goal. Considerable efforts have been made recently to develop early warning systems. However, these methods lack a direct and online measurement of the spores that attack crops. A novel disease information network has been implemented and deployed. Spore sensors have been developed and deployed. The measurements from these sensors are combined with similar measurements of important local weather readings to generate estimates of crop disease risk. It is combined with other crop disease information allowing overall local disease risk assessments and forecasts to be made. The resulting data is published through a SPARQL endpoint to support reuse and connection into the linked data cloud.

Keywords: investigation study assay, sensor network, online sensors, data queries, crop disease assessment, web semantics

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1 Introduction

This paper describes an ontology for describing data collected from sensor networks for monitoring fungal infections of food crops. There is and there will continue to be rising global food demand due to the increased global population. This generates the need to maximize the productivity of farmland. This need is reinforced by the fact that the availability of arable land has stopped increasing in recent years (UNFAO, 2009). Thus it is necessary to assess options for minimizing losses in food production, so that crop yields can be maximized. Failure to act decisively on meeting the rising global food demand will lead to food shortages and famines.

An obvious and large problem is pre-harvest losses in crops, where it is estimated that 42% of potential crop production is lost during the pre-harvest phase due to crop diseases (IAPPS, 2011). Attacks on crops by diseases typically cannot be stopped once started, but crops can normally be protected against attacks from particular diseases (Chaube and Pundhir, 2005). Hence, the most effective means of disease control is to treat a crop with protective chemicals around critically sensitive periods of the pathogen lifecycle, such as germination. Timing the application of crop protection treatments to when active spores are present and when there is a likely hood of disease outbreak, will give the best return to the grower through better yields and optimised inputs.

There are a number of information sources that can help identify an impending outbreak of disease in a field.

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Firstly, it is the weather, both current and future. As the diseases need warm and wet conditions to proceed with their attacks on the crops (USDA-NPA, 2011) and being located downwind of recent crop attacks would indicate that diseases are in the air blowing in the crop's direction. Secondly, the history of the field indicates whether that field is a "hotspot" or high risk area; factors such as soil composition and previous disease outbreaks are important in assessing the likelihood of future attacks (USDA-NPA, 2011).

A lot of previous work has been done in measuring some or all of these factors and transmitting those measurements to a decision making facility quickly, to allow crops to be protected in time (Koch et al., 2007; Varraillon, 2011; Twengstrom et al., 1998; Clarkson et al., 2007). However, previous attempts at disease warning systems have fallen short on a number of key points. Firstly, direct measurement of the disease entity itself is often omitted or is measured offline by a mechanism such as a petal kit test (SMoA-Canada, 2009) when it is included. Secondly, actual live weather measuring points can be far apart, leading to local interpolation errors (MetOffice-UK, 2004).

These weaknesses can be overcome with a disease sensing network that can provide direct and live measurements of the presence of disease bodies in the air in the vicinity of the crop, as well as providing a sufficiently dense network of live weather information to eliminate significant interpolation errors. In this paper, we report on the deployment of the third generation sensor network that has been deployed at five sites in the United Kingdom, with the data published through a SPARQL endpoint as linked data and viewable through a web portal.

The sensor data allows imminent attacks of disease to be quickly identified, and for rapid deployment of crop protection chemicals to fields in danger, which will mitigate or even prevent crop losses, thus results in much greater crop yields and food supply. This implies collection and analysis of large amounts of data, and most importantly to have a reliable description on "what these data are". An ontology, that reuses the SSN (Semantic Sensor Network Ontology) (LeFort et al., 2011) and ISA (Investigation, Study, Assay Tools) (ISATools, 2011) Ontologies, is used to provide a framework for describing data from sensor networks (Section 3). The ontology describes the hardware, the data types, units, the entity being monitored, as well as being able to supply a framework that can manage individual readings all the way to widescale "disease investigations" over a large area and large time-scale.

The goal of the research is to devise and implement a data collection system using widely available and economic hardware that can provide enough up to date information for an estimate of the likelihood of the presence of sufficient disease spores to which may cause substantial loss of crop yield to a particular grower, and furthermore to provide a quantitative estimate of the extent of damage caused due to the presence of weather conditions favorable to disease development based on both existing and novel infection models such as that of Koch et al. (2007).

2 System applied

This section describes the deployed sensor network, the middleware for transmitting the data to a central repository where it is made available through a SPARQL endpoint, and the web application that is used to present the data to the end users. The sensors have been deployed at a variety of locations in England and the central repository is hosted in the University of Manchester.

2.1 Information sensors

A combined sensor capable of detecting and measuring crop disease presence and also a range of important weather phenomena has been deployed in the United Kingdom's Oilseed rape growing regions. The sensors were bespokely constructed from standard equipment that is widely available by Burkard Manufacturing (Ricmansworth, Hertfordshire, UK). The sensors were deployed at Rothamsted Research (Harpenden, Hertfordshire), on two farms managed by Velcourt Farm Management (Sleaford, Lincolnshire and BaptonManor, Wiltshire) and on two farms managed by Syngenta (Jealott's Hill, Berkshire and Fulbourne, Cambridgeshire).

The sensors detected the concentration of spores in the air, the air temperature and the air humidity in the crop canopy, as well as crop leaf wetness, wind speed, direction and the internal temperature of the spore sensor. By making a direct measurement of disease spores, these sensors have a clear advantage over existing live information networks. The sensors take a measurement every ten minutes which is cached locally on the sensor. Each hour the sensors transmit text messages via SMS over the O_2 or Vodafone networks. The messages are received by a terminating number provided by BT and converted into comma separated value text files using proprietary software and transferred by secure FTP to the central database. As a backup, each sensor stores 1 day of data in memory buffer. This will allow the text messages to be resent in the event of a communications failure of less than 24 hours duration.

2.2 Sensor network and central database

The data from the sensors is sent to a central repository where it is loaded into a PostgreSQL database chosen for its ability to support multiple rapid SQL queries of small subsets of data. Before loading, the data collected from the sensors is transformed into S.I. units (BIdPeM, 2006) according to calibration specifications provided by Burkard Manufacturing. All datafiles carry a timestamp in the Coordinated Universal Time (UTC) ISO 8601 (ISO, 2004) and the longitude and latitude of each sensor node was predetermined for the deployment at the beginning of the crop flowering season. Sensor data was loaded onto the database by a customised python script with a listening function activating every hour.

Online weather forecast data from the Syngenta Global Weather Web service was provided by daily secure FTP transfer from the Syngentaserver in Switzerland. Satellite image data from the Disaster Management Constellation International Imaging (DMCii) was also provided by secure FTP transfer from their server in Guildford, Surrey, UK. These readings are also transformed into S.I. units and the same temporal and spatial co-ordinate frameworks. The weather forecast data was loaded into the database by a customised python script with a listening function activating every hour. The satellite image data was loaded manually into the database as it was not received regularly.

The database also holds permanent and semi-permanent data such as soilmaps, site histories, as well as sensor commissioning, maintenance, self diagnostic and decommissioning records that were uploaded by the installation and maintenence engineers. These were manually updated periodically or on extraordinary occasions. There is the facility for authorised persons to edit the database, while the ordinary user will only be able to read specified portions of it.

Missing data due to sensor failure was dealt with by retaining the Syngenta Global Weather service data on the database. In particular the forecast of spore concentration was handled by applying the “Raiso-Sclero” model (Varraillon, 2011) on the forecasted and measured data.

There were two essential purposes to be served by the data and as such the data needed are stored in two different ways. The data needed to be stored in relational database form to accommodate conventional SQL queries that will be required by the website application programming interface. Furthermore, the high suitability of PostgreSQL to a very high frequency of small transactions makes it an ideal forum for ingesting the sensor data and other the external data.

However, there are key weaknesses in the conventional relational database and SQL approach. The main one is its inflexibility; a relational database is designed to store specific data structures and to accommodate specific types of query on that data. Thus, data structures and queries of types that have been anticipated during the database design will be very efficiently processed. However, attempts to store data of different structure or make an unusual query could result in a very slow response or even database failure.

As such, a more flexible version of data storage and data querying was required, especially when there will be a need for data reuse by a variety of interested parties such as sales managers, marketing managers and weather monitoring officers. Each of them has their own potentially unique requirements, and as such may wish to make vastly different queries of the data and to combine queries of this data resource with queries of other data resources, such as sales records.

This requirement for a more flexible data resource was met by frequently dumping the database contents into an RDF Triplestore which can be exposed over the internet and queried with a language not dissimilar to SQL called SPARQL. By storing the data in the form of subject-predicate-object or “Triple” form, it provides a common framework that simplifies data integration from multiple datasets (Gray, Gray and Ounis, 2009).

The D2R mapping language (http://d2rq.org/d2rq-language) was used to translate the relational data as RDF. Mapping files created with D2RQ were used to generate RDF data consistent with the PostgreSQL database. Two repositories were created: “Quantity” and “Non-Quantity”, where the Quantity repository, i.e. the measured and predicted values for the features of interest was continuously refreshed with a customised bash script operating on an infinite loop with a 24 hour sleep step. The Non-Quantity repository would only change very occasionally, so it was refreshed manually invoking a similar bash script without an infinite loop if required. The exposure over the internet was performed with the software “Sesame” including the Graphical User Interface “Workbench” which includes a convenient SPARQL endpoint: (http://syieldserver.eee.manchester.ac.uk:8080/openrdf-workbench/repositories/NONE/repositories). This now allows query results to be easily combined with similar SPARQL queries on other repositories of interest.

2.3 Web application implemented

The sensor data were exposed through an API for application developers. A web application, which uses the paradigm of layering readings on a map, has been developed (Figure 1). Regional summary data can be shown, or users can zoom in on the data of interest.

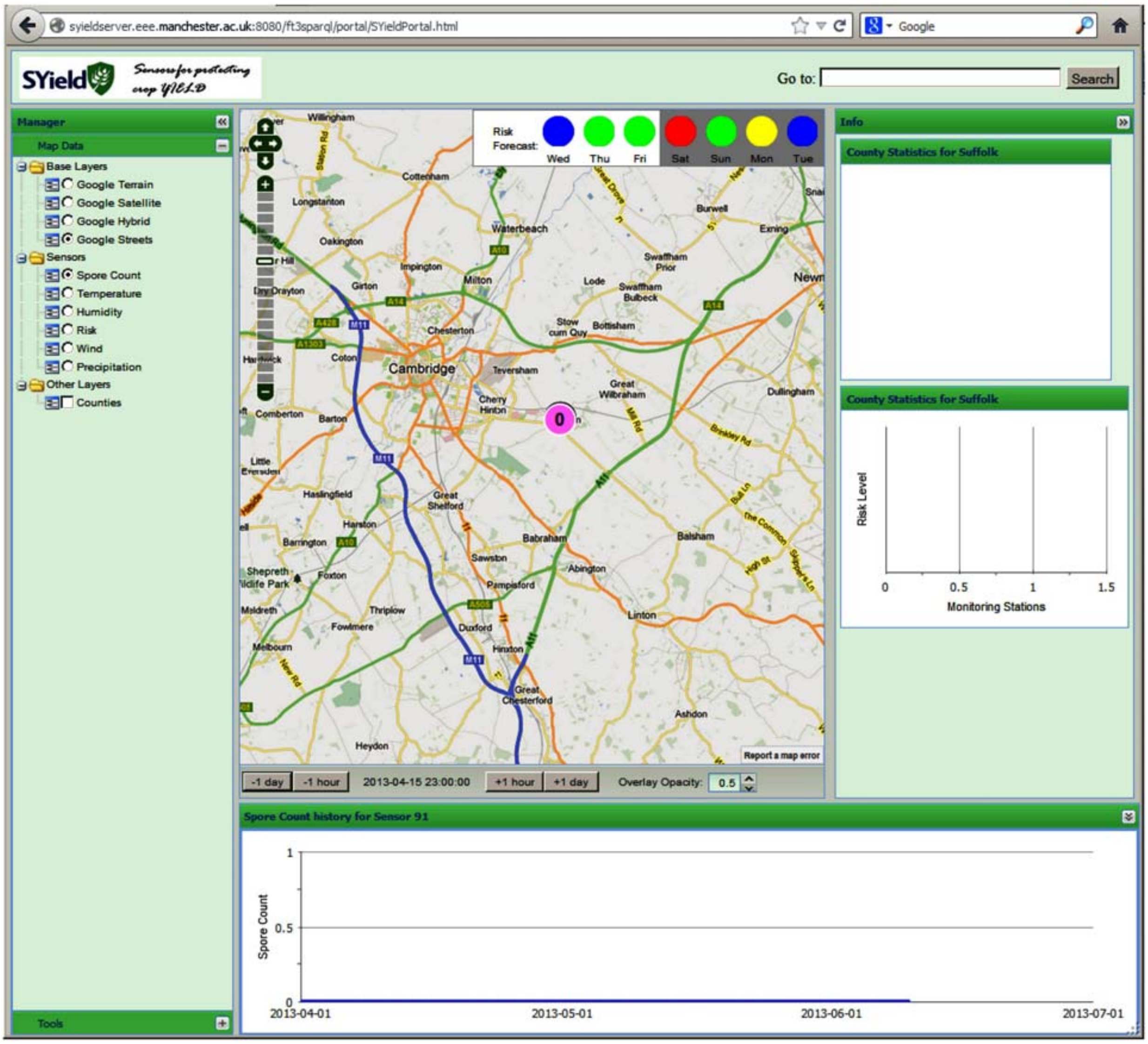

Figure 1 Screenshot of the web application

The API also facilitates the registration of alerts for long running monitoring queries over the data. For example, email and SMS alerts can be sent when danger levels of spores are detected by the sensors or a node malfunctions.

3 Ontology creation

Features of the environment that are considered important to a local assessment of the likelihood of crop disease damage in the near future together with details of the sensor deployment and the information system are captured using an ontology. Each element of the ontology describing these data fulfilled the need to have a clear meaning and have clear relations between all of the other elements. Such well defined meanings are essential if any of the system changes, such as sensor hardware used, resulting in a different calibration curve, detection limit, survival range etc., if additional features are deemed important in the future, a different weather forecast supplier is used etc.

An ontology, written in OWL, was developed to model the sensor data and the information system. The ontology implements the Investigation-Study-Assay concept (ISATools, 2011) that has been used to gather experimental data from systems biology and uses the Semantic Sensor Network Ontology (LeFort et al., 2011) to capture details of the deployed sensors. Details of these approaches together with an overview of our resulting ontology are discussed in the following sections.

The Investigation-Study-Assay ontology (ISA) (ISATools, 2011) has been developed to model biological assay experiments and the investigations in which they are a part. At a high level, this ISA model captures the rather broad term experiment at various granularities. An assay might be an individual measure and an “experiment” typically involves many such assays. As individual assays can be unreliable, replicates are gathered as observations. A series of observations are grouped together in a study; several observations of several types will make a study, as an “experiment” typically involves the gathering of many observations in order to address a question. Finally, an investigation may involve many studies in order to address a broader research question.

The Semantic Sensor Network (SSN) Ontology (LeFort et al., 2011) has been developed by the W3C Semantic Sensor Network Incubator Group (http://www.w3.org/2005/Incubator/ssn/accessed 27 March 2013). The SSN ontology uses an observation centric model for capturing sensor data. Each sensor reading is modelled as an observation that consists of the values captured by the sensor, the sensor makes the reading and the feature of interest is being observed by the sensor. The SSN captures details of the sensors – their hardware and the deployment – although it needs to be extended to capture domain specific notions, e.g. it has the notion of a Sensor, but not of a Wind Speed Sensor or a Spore Sensor. Lefort et al. (2011) have provided the Agriculture Meteorology Sensor Network Ontology that extends the SSN ontology with many of the concepts we require for the Spore Sensor Network deployed in this work.

An overview of the crop disease information system ontology (http://www.cs.man.ac.uk/~stevensr/ontology/CombinedOntology3.owl accessed 27 March 2013) is given in Figure 2. We have adapted the Just Enough Results Model (SysMo, 2011) from the ISA approach – assay, observation, study and investigation – to represent the sensor network data and their processing. We have re-used this breakdown of an experiment to capture the range of data captured by a sensor network and the various aggregations that take place. The devices used in an assay lie inside this ISA model. For the hardware aspects of the scenario, the ontology re-uses the SSN-based Agriculture Meteorology Sensor Network Ontology (LeFort et al., 2011).

3.1 The assay

In this scenario, an assay is a single measurement event where a feature of interest of the environment makes contact with the sensor and will stimulate it in a quantifiable way. The sensor response is then passed onto a recording device. The sensor response is raw and is a 16-bit unsigned integer. The sensor response is centrally recorded in the node memory. The fact that the sensor response will be a raw number strongly underlines the need for the inclusion of equipment calibration curves in the ontology to ensure its correct equivalent in S.I. units is described.

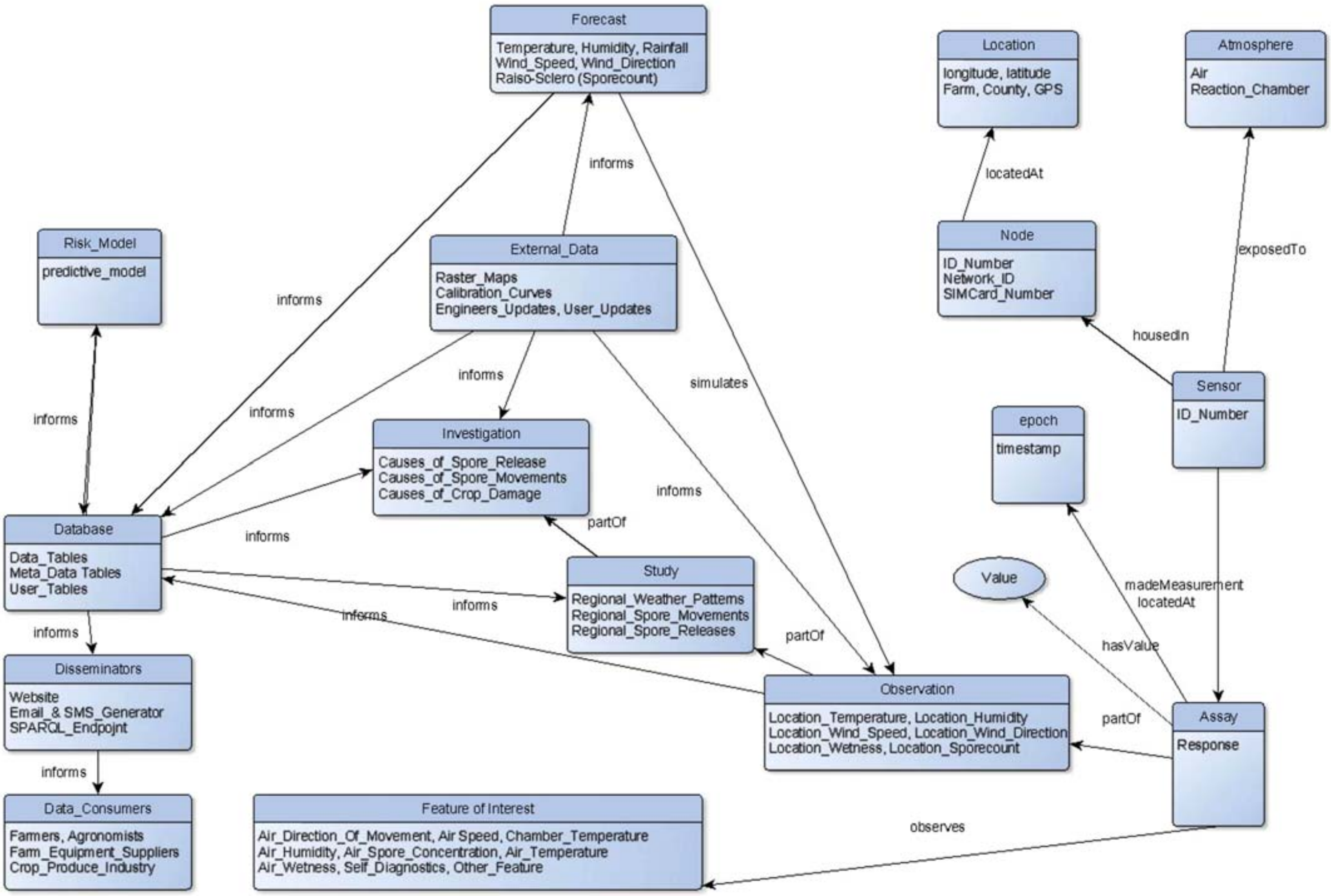

Figure 2 An overview of the crop disease information system ontology

3.2 The observation

A single measurement event or assay is not a good reflection of the conditions in the local environment that is being measured: a variety of features are required to get a complete picture of what is happening in the environment (spore concentration, temperature, humidity etc.). In addition, some features such as wind direction can fluctuate strongly, meaning an average over a period of minutes is needed to get a reliable measurement. As such, a cluster of assays gives an observation of the environment in a particular place (surrounding the sensors) at a particular time. An observation is created when the node memory reports its 10 minute average of all features of interest. The observation is then transmitted in batches of six reading via SMS to the central repository.

3.3 The study

A single observation does not reveal any pattern of events or trends. To do this, a cluster of both spatial and temporal observations is needed to form a study of the environment. This would involve something like collecting all the temperature observations in a certain area for a 28-day period and monitoring the bulk increase over that period.

3.4 The investigation

A single study only examines one pattern or trend. To get an overall picture of the situation, what is needed is an investigation. This will consolidate the patterns and trends in all of the measured features and extract a summary measurement; in this case, it will be the risk of disease affecting the vicinity of each sensor over the disease season. Previously forecasted values from the Raiso-Sclero (Varraillon, 2011) model can be used to provide in-fill for missing values.

4 The OWL model

The ontology's objective was to ensure that the potentially enormous data requirements can be tracked efficiently and effectively. It was desired that the information required can be quickly and safely deposited onto a standard database and quickly and safely be brought to a point of consumption (website, SPARQL endpoint, SMS, email etc). The size of the data load on the network means this is not a simple question, as the number of bits and bytes used for data generation, transmission and storage must be kept to a bare minimum to avoid slowing down the data processing. Taking on board these competing concerns and starting from the ontology of (LeFort et al., 2011) the following model was built:

- Features of Interest: These are the phenomena that are measured in each assay and that are considered important factors in an overall disease risk assessment along some other measurements that can provide additional context to the measured values.
- Hardware: These are the physical objects that are needed to perform assays. This consists of the sensors, the nodes in which they are housed and the network that provides the conduit for the information to flow to the central server.
- Information: These are the labels needed to uniquely identify assays, the data, sources, stores, sinks and transformers. This also clearly defines the entities that create data, those that are consumers and those that are conduits of data transmission with or without modifications to the data as it passes through.
- Input: The entry of data into the various data vehicles from the sources all the way to the information sinks. The data enters as individual assays which are combined into 10 minute averages (the observations), which are then combined to monitor patterns (the studies) and eventually combines to monitor general trends (the investigations).
- Output: The receipt of data into the various data vehicles from the data sources all the way to the information sinks.
- Landmass: The named physical sites where assays take place. This will be the farms that host the node networks including the fields that host the individual sensors. It will also be the landmasses that are designated as counties for the purposes of government administration in the United Kingdom.
- Role: What each entity does with the data i.e. create it, pass it on, modify it or digest it. The sensors supply data which is transmitted via the node networks and the weather forecasts and satellite raster maps also supply information directly to the central server. The data is transformed by the database ingestion software and consumed by the database where it is exposed to the world wide web via the website API and SPARQL endpoint.

This model is shown in Figure 2. The model shows how a raw data point is created by a stimulation at the interface of sensor and atmosphere, how this raw data is passed through the node into the node network and through the node network into the Geographical-Time-Information system, to transform it into S.I units in geographical and temporal terms and also through the specification matrix to transform the raw sensor response into S.I. Units.

The most important aspect of this ontology is to cope with deviations from the original specifications of the sensor network. For example, if a new generation of humidity sensor is installed into the next batch of nodes with a different calibration curve, then the facility to apply the new transformation polynomial on the raw data is present. Similarly, if a new generation of spore detector with a shorter time lag is installed into the next batch of sensors, the correct estimates can be made.

5 Related work

The principal point of comparison is the Semantic Sensor Network ontology of the W3C semantic sensor network incubator group (LeFort et al., 2011) which was the starting point for this ontology. (http://purl.oclc.org/NET/ssnx/ssn). This is an ontology fully describing the operation of an infield sensor. It describes eight types of entity: Abstracts (not in space-time), Events (a physical, social or mental process), Information Entity (a piece of information that is realized or not), Object (physical, social or mental substance), Quality (a dependent aspect of the entity), Feature of Interest (abstraction of a real phenomenon), Input (information provided to a process) and Output (information reported by a process). Among those the first five provide highly detailed description of how sensors are stimulated by their environment by natural phenomena and how the sensor responses should be interpreted and meaningfully and robustly quantified. Without such a comprehensive and detailed ontology the raw signals could never be converted into S.I. units with confidence.

In terms of sensor deployments in agricultural situations there is a comprehensive review provided by Ruiz-garcia et al. (2009) which introduces important recent examples of how sensors have been used to characterize the agricultural environment and provide information that has substantial predictive and informative value. Typically the objective is to estimate features of interest such as temperatures, humidities, moisture levels, concentrations of nutrients or components, electrical conductivity, light intensity. This breaks new ground by using a sensor for the direct measurement of the concentration of viable disease spores in the crop canopy.

6 Ontology testing and validation

Starting from the ontology of LeFort et al. (2011), new material was added to reflect the uniqueness of the current network of sensors and backup data sources and to reflect the needs of the users who will be probing the database. This does underscore the need for a robust ontology as errors or shortcomings discovered at the commercialisation stage would in all probabilities not be fixable and would require redesigning the sensor network at massive cost.

The Ontology has been rigorously tested under experimental conditions whereby data has been collected from a variety of live sources (sensor nodes, weather forecast supplier, and satellite image supplier) and it was rapidly and successfully deposited into a central repository in the correct geo-temporal location in S.I. Units. It was also rapidly exposed over the internet in two convenient formats (the web portal and SPARQL endpoint). Thereby it allows growers to make critical decisions regarding crop protection strategies in a manner that is more informed than previously.

7 Conclusion

We have shown that the Investigation-Study-Assay based model from systems biology is broadly applicable to sensor networks for monitoring crop diseases, as the recordings of the results of assays in order to answer scientific questions is a broadly applicable paradigm. The different levels of the Investigation-Study-Assay model capture the various levels of granularity of data, and its aggregation, required for monitoring important factors in the process of an investigation into crop-infection. The final ontology drew on existing established principles of Investigation-Study-Assay and Agriculture-Meteorology-Sensor-Network.

The sensor network and central data repository have been successfully deployed to monitor the conditions on five farms in the south-east of England. The deployment and the sensor readings have been modeled using the ontology presented in this paper. Currently the ontology is purely functional and models a wireless sensor network. The ontology described and its application scenario is relatively simple, but is entirely appropriate; a significant requirement is that data can be described and this ontology fits this need.

The successful application of this ontology lays the groundwork for a successful attempt at gaining intimate knowledge of when crop diseases are likely to strike. Armed with this knowledge, the end user – whether it is a farmer, agronomist, sales manager, marketing manager or supplier of crop disease mitigation equipment – can extract the data of interest. This has the potential to salvage 42% of potential crop yields and take a major step towards increasing food supply which will become a critical issue as the world population increases. Furthermore, this ontology has great potential for re-use in future sensor networks that attempt to achieve similar objectives.

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