Computers, Environment and Urban Systems 48 (2014) 28–34

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/compenvurbsys

# An open source software approach to geospatial sensor network standardization for urban runoff

Andrew J. Rettig[a,*], Sumit Khanna[b], Dan Heintzelman[c], Richard A. Beck[a]

[a] Department of Geography, University of Cincinnati, Cincinnati, OH 45221, United States
[b] College of Engineering and Computer Science, University of Tennessee at Chattanooga, Chattanooga, TN 37403, United States
[c] School of Planning, University of Cincinnati, Cincinnati, OH 45221, United States

A R T I C L E I N F O

*Article history:*
Received 25 July 2013
Received in revised form 5 May 2014
Accepted 13 May 2014
Available online 17 June 2014

*Keywords:*
Sensor networks
Open source software
Urban runoff
Open Geospatial Consortium

A B S T R A C T

In this paper, we implement a geospatial sensor network for monitoring a green technology stormwater runoff site. The sensor network uses OpenWRT, an embedded Linux operating system, and other open source software, to create a modified router for reading Maxim's 1-Wire™ protocol, queuing and transferring standardized sensor data while enabling location and time. The modified router created the bridge between the sensor protocols and the middle-level software to provide reliable data to both the sewer district and the Environmental Protection Agency. Representational State Transfer (REST) is used in the design philosophy of the client and server open source software for transferring the data from the embedded systems to the server level for storage and publication. The use of open source software not only creates a more affordable network but lowers the entry barrier to sensor networking and enables developers for continued innovation and standardization.



## 1. Introduction

Stormwater and wastewater management has been a crucial part of urban planning since the beginning of urban development. Engineers design city infrastructures to either carry water away through city streets and water ways or capture the water for reuse. Stormwater is the result of water runoff from impermeable surfaces during precipitation, in contrast to wastewater that is discarded after human use. It is not uncommon for stormwater and wastewater to be combined into a single system, combined sewer systems. Peak flows during rain events can cause these systems to overflow. Accurately predicting stormwater volume with variable rainfall is crucial to preventing flooding. However, stormwater is rarely measured due to a lack of affordable and standardized sensor networks. In the rare cases where stormwater is measured, it is at a few fixed locations. Alternative means are beginning to be created for more widespread measurement throughout the city. Distributed fixed and in some cases mobile stormwater measurement and water quality stations are being created to supplement fixed locations (Ruggaber, Talley, & Montestruque, 2007 and Sempere-Paya and Santonja-Climent, 2012). But complete city coverage at the household level is impractical both financially and technically, primarily due to a gap between sensor protocols and middle-level software. Sempere-Paya and Santonja-Climent, 2012 described the next step for urban wastewater sensor and management systems as the merging of "Internet of Things" and "Smart Cities" for providing the automation of data. The first step in their plan was for a modular architecture that is not tied to the equipment manufactures at geographically disperse locations.

In this paper, engineers and researchers from the University of Cincinnati implemented a modular architecture for monitoring stormwater runoff. The geospatial sensor network uses the embedded Linux operating system, OpenWRT, for reading, storing and transferring sensor data. The open source implementation bridges the gap between sensor protocols and middle-level software enabling innovation within an end-to-end sensor network. The structure of this paper includes: previous work in sensor networking highlighting open source developments, an introduction to the study area and project, and the technical architecture of the network focusing on the OpenWRT router. The OpenWRT router enables the affordable and scalable modular stormwater sensor networking implementation so the paper describes building the embedded Linux kernel and flashing the router.

* Corresponding author. Tel.: +1 513 707 2685.
*E-mail address:* andrewrettig@gmail.com (A.J. Rettig).

http://dx.doi.org/10.1016/j.compenvurbsys.2014.05.003
0198-9715/

## 2. Previous work

### 2.1. Sensor networking

Traditionally sensor network innovation and development occurs within military research. The Sound Surveillance System (SOSUS), considered one of the first sensor networks, is a network of underwater acoustic sensors that was installed in the 1950s as a result of research from World War I and World War II (Chong & Kumar, 2003). SOSUS today is part of a larger military sensor network. As research continued into the 1980s, work was done under the Defense Advanced Research Projects Agency (DARPA). Today, the most advanced sensor networks are still being developed by the military but with increasing affordability, sensors and sensor networks are economically deployable. With the development of open source modified routers with a GNU/Linux Operating System, user community innovation will help accelerate and improve deployment. Sensor deployment faces many challenges including: power consumption and battery issues, storing of data, streaming data, connectivity, wifi meshing, sensor availability, and weather and environmentally resistance. Allowing greater user control, incentive and innovation will continue to improve sensors, sensor networks and standardization. Bob Gourley founder Crucial Point LLC, top 100 "Tech Titans" list and former member of US Department of Defense, cyberdefense group recently stated "Open source tools are becoming the infrastructure that every company is putting themselves on," (Vance, 2013).

Open source software, for sensor networks, has been developed by several research groups. The Web Service Access Framework (OX-Framework) has been developed by 52° North to assist with clients connecting to the Open Geospatial Consortium (OGC) services. The Framework assists with the formidable task of trying to connect a variety of different sensors to the client for visualization (Bröring, Jürrens, Jirka, & Stasch, 2009, Jirka, Bröring & Stasch, 2009). Effective clients are needed for comparison and analysis of the data. The OX-Framework offers a reusable design that can be altered. Quality Assurance/Quality Control (QA/QC) is very important with sensor networks as complications arise at various levels within the network. Workflow systems can help manage the data, as well as can be used for data exploration and analysis. Examples of open source data management systems are VizTrails, Taverna and CUAHSI information system (Ames et al., 2009; Callahan et al., 2006 and Hull et al., 2006). Analytical tools such as R, Kepler or GCE Matlab are often incorporated into the data flow as well (Altintas et al., 2004). The most relative open source development within sensor networking is Data Turbine. Data Turbine is a robust real-time streaming data engine with three basics parts; First Data Turbine connects to sources, or sensors, to stream the data; Second, it connects to servers for storing the data; Third, it connects to sinks that receive the data for quality assessment and quality control (QA/QC) or visualization (Fountain, Tilak, Shin, & Nekrasov, 2012). Recently, Data Turbine was ported onto an android platform sensor pod for easier sensor integration and additional processing closer to the sensors. We chose not to use the android platform of Data Turbine for a more affordable OpenWRT Linux based system suitable for wired Ethernet connections.

OpenWRT is GNU/Linux for embedded devices with a writable file system with package management called ipkg, Itsy Package Management System. OpenWRT was a development specifically for writing a GNU/Linux firmware for a router, specifically the WRT54G Linksys router (Innes, 2005). Linksys released the WRT54G router in 2004 running an embedded version of Linux. Once Linksys released the code, the WRT54G router code be customized and enhanced by the open source community (Innes, 2005). However, OpenWRT was written as a new complete firmware for the router. OpenWRT was different from other firmware for the WRT54G, because it did not attempt to be an all-inclusive system with only a minimal Linux install (Innes, 2005). This firmware approach has attracted many programmers over the years and attracted our engineering team with its applicability as a sensor data logger and transmission device.

## 3. Methods

### 3.1. Study area

Stormwater runoff and resulting combined sewer overflows are one of the largest water polluters in the nation (EPA, 2012). Cincinnati has recently negotiated a federal consent decree (legally binding agreement between city, state, and federal agencies) that sets combined sewer overflow pollution reduction goals to two billion gallons by 2018 (EPA, 2013). Our geospatial sensor network was developed in conjunction with the Green Learning Station Project (GLS) at the Cincinnati Civic Garden Center. The Green Learning Station Project was part of the Metropolitan Sewer District of Greater Cincinnati (MSDGC) green technologies examination of pervious pavements, bioswales and rain water harvesting for reducing stormwater runoff (Fig. 1). Green infrastructure sites have been implemented throughout the city as "early success" sites to examine their reliability and effectiveness to meet the two billion gallon reduction goal (EPA, 2013). Our team of engineers, UC@GS, was formed in conjunction with the Cincinnati Civic Garden Center and the University of Cincinnati to develop a real-time and location in situ sensor network for monitoring stormwater runoff from the test site. The sensor observations would be used for evaluating the green technologies by the MSDGC and the Environmental Protection Agency.

### 3.2. Site design

The sensor network to be implemented would be an end-to-end network, monitoring the water flow and quantity of the 5 permeable pavers and 1 control pavement. Weather stations were also incorporated in the network, installed on site to record the rainfall for evaluating the permeable pavers. Fig. 2 is a diagram of sensor monitoring infrastructure for water quantity and flow at the Green Learning Station. Our prototype stormwater monitoring sensor network consists of: a water pump and water meter in each manhole, a counting sensor on each meter, a temperature sensor in the manhole, Cat5 burial grade cable to the Green Learning Station, a USB to 1-Wire convertor, a USB hub, an optional GPS, a modified router, Ethernet connection, and an offsite server cluster (Fig. 2).

### 3.3. An open source sensor network architecture for stormwater runoff

Sensor networks have three generalized levels of infrastructure, (1) a low-level physical layer of sensors and monitoring infrastructure that translates the sensor data into a common format for storage and transmission, (2) a middle-level layer of hardware and software that receives the data and parses the data in a database, and (3) a high-level hardware and software for distributed visualization and analysis in the form of web services (Fig. 3). The low-level is composed of a variety of proprietary and open protocols for communicating with the sensors. This level of infrastructure includes sensors connecting to a modified router that receives and translates those data from a variety of formats to a standard XML format and transfers the data to the server. This low-level set of functions is necessary to construct the next generation of plug-and-play sensors. The low-level of our technology stack used