CYBER-PHYSICAL ARCHITECTURE, CLOUD COMPUTING AND MOBILITY: THE VERTICAL DESIGN OF A SENSOR-BASED, MICROCONTROLLER SYSTEM INCORPORATING PREDICTIVE ANALYTICS

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Abstract

Cyber-physical computing is enabled by low-power, inexpensive sensors and processors. This paper reports on the results of defining the computing architecture that exploits a sensor-base microcontroller architecture in a distributed fashion in the physical environment to solve a problem in the sustainability sector. In addition, a project implementation of the architecture is presented.

The aim of the research was to solve two common problems. First, how to make more efficient the collection of distributed recycling within a city or organization. Second, how to quantify recycling programs at a finer level of granularity. The solution developed to rectify these issues took the form of the Charleston Digitally Assisted Recycling (CDAR) project.

At the core of this is the Arduino[1] single-board microcontroller. Coupled with an ultrasonic distance sensor attachment, the Arduino can detect and measure distances from two centimeters up to three meters, to the centimeter. Using this the capacity of recycling bins can be determined by measuring the space between the sensor and the refuse. The shorter the distance, the fuller it is. By attaching an Arduino to each recycling bin within a distributed network of several and using readings obtained from CDAR software, written in Java, an accurate (±1 cm) measurement of bin capacity could be obtained. This data could then be passed along to the organization in charge of recycling to notify them when the bins were predicted to be full and ready to be emptied. From these measurements, along with predictive analytics, it could be determined when next the network of bins were thought to be full. Thus, a more efficient recycling schedule can be devised, as well as allow for a new level of precision in measuring recycling at a much finer granularity than is taken into account in today's sustainability systems.

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[1] Arduino is a trademark of Arduino Team

Contents:

Introduction

The CDAR project was born of a union between the fields of Sustainability and Cyber-physical computing and the desire to solve problems of the former through an implementation of the latter. These problems are the creation of an efficient cycle for distributed recycling and obtaining measurements of recycled material at a finer granularity is presently taken into account. The significance of these is that successful application of a solution would allow for several benefits. An efficient collection cycle creates reduction in the carbon footprint produced by trucks tasked with collecting the recycling as well as in their fuel consumption. With more precise measurements more precise data of total recycling becomes available for report and study. Presently, recycling measures are done only by the ton. The precision offered by this project provides a much greater degree of accuracy across the dimensions of space (the precise location of where refuse was collected), time (the specifiable frequency of collection over a period), and volume (how much was collected). Enough measurements gives way to the possibility of following trends to estimate when next recycling bins could be full. With this project both a solution and these results are possible.

The tool chosen to implement the solutions for these tasks was the Arduino, a single-board microcontroller notable both for its accessibility and low cost. In tandem with an ultrasonic distance sensor and hardware that allows for network interfacing (both ethernet and wireless), a system was developed in Java that could be placed within recycling bins and accurately detect the amount of refuse within. The placement of multiple devices within several bins across an area creates a linked network capable of being monitored remotely. This collection of units forms the cyber-physical aspect of a recycling system which in turn provides the solutions to our sustainability goals.

Sustainability

The notion of Sustainability is a broad one that covers the idea of continuity and how to achieve it. The three major components of this field are the environmental, social, and economic aspects. The environmental generally describes what of the environment is being considered such as pollution, conservation, or energy. The social describes what relates to health, community, or working conditions. The economic aspect concerns qualities such as jobs, wages, trade, etc. Essentially, for any given sustainability argument, the environmental aspect details what of the environment is involved, the social describes how it affects people, and the economic pertains to costs. Sustainable development features two key concepts as defined by the United Nations. These are “the concept of ‘needs’, in particular the essential needs of the world’s poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment’s ability to meet present and future needs.” [2] Supporting these two points are what are considered the major pillars of the discipline, economic development, social development, and environmental protection [1]; the three of which correlate with the main tenets of sustainability itself.

Since the 1980’s, however, the term ‘Sustainability’ has been increasingly used in the context of humans and their relation to the planet Earth, specifically describing the concept of ‘sustainable development’, which was defined by the Brundtland Commission of the United Nations as “...development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” [1] The history of the concept starts from early human dominated environments up through modern ones, following societies that experienced success in surviving within their regions, and ranges from technologies such as fire up through fossil fuels. These societies that survived whatever pressures that ailed them experienced sustainability.

Periods such as the 1970’s and mid 20th century showed examples of sustainability issues entering the public consciousness with energy crises within the former and an increase in public knowledge of fossil fuels within the latter, and with the 21st century came a greater, more global awareness of the consequences of greenhouse gasses. With greenhouse gasses came the notion of global warming, and that coupled with an energy shortage stemming from the depletion of finite fuel resources created a demand for new technologies that adhered to sustainable development’s core concepts. It is from this need that cyber-physical systems and their research grew.

Cyber-physical Systems

Cyber-physical systems (CPSs) are systems emphasizing the union and coordination of a system’s computational and physical elements. A system is defined as a set of components, independent of one another or working together, forming a cohesive whole. Cyber-physical computing, then, is the exploration and application of these systems. An important distinction between CPSs and their precursors, embedded systems, lies in their design. While both feature computer systems that control specific functions of larger ones, the key characteristic that makes CPSs stand out is that a mature CPS will be designed as a scalable, distributed network composed of multiple devices obtaining and trading information. Additionally, embedded systems typically are designed as closed environments with their computational elements isolated from the environment. Contrary to this, most CPSs do not exist in such an environment and as such must be designed more robustly to prevent failures.

One of the earliest examples of such systems was the Autonetics D-17 guidance computer embedded in the Minuteman missile circa 1961. The D-17B computer weighed in at 62 pounds and contained a myriad of electrical components. Not long after developers turned to the creation of microprocessors by way of implementing a central processing unit (CPU) into an integrated circuit, the first of which was the Intel 4004 released in 1971 [3]. Eventually, microprocessors were integrated with memory, input, and output components to form microcontrollers, which today exist at the heart of many embedded systems.

Arduino

One particularly notable microcontroller is the Arduino.[4] The Arduino is a single board microcontroller developed in 2005 in Ivrea, Italy, with the original intent of creating a cost-effective device, cheaper than already existing prototyping systems, for students to utilize in interactive
design projects. Prior to its invention, microprocessors were both costly and obtuse to utilize out of the box. The Arduino is both cheap and provides a simple integrated development environment (IDE) for users to interface with. Its ongoing popularity [5] has brought it further and further into the public consciousness and made it a popular choice for educators [6] looking to teach embedded systems or the programming of as well as numerous do-it-yourself projects for hobbyists. [7]

A microcontroller is a miniature computer within a single integrated circuit containing a processor, memory, and programmable input/output peripherals. It was created by two founders, Massimo Banzi and David Cuartielles, who initiated the project as a fork off the Wiring platform. Similar to the Arduino, Wiring is also a prototyping platform; both of which share a common precursor in the Processing programming language. [8] Being that Processing is open source, so too are Wiring and Arduino, meaning essentially that their software is freely available to view, download, and alter, so long as the original creator is given credit. Several variations of open source licensing exist with various restrictions on how much any offshoot projects are allowed to withhold from being open source themselves.

Several variations of the Arduino exist, but two of the most common official offerings from the Arduino Team are the Arduino Uno and its larger sibling, the Arduino Mega 2560 [9]. The primary components of these boards include the main processor, a USB serial port, a power supply, and expansion connectors. The processor of choice for the Arduino boards is the Atmel[1] AVR[2] ATmega328, which is derived from the original Arduino processor, the ATmega8. [9] This chip can function from a range of 1.8V to 5.5V, making it well-suited for battery-powered applications. It has a max clock rate of 4MHz (million cycles per second) at the lowest voltages but can max out at 20MHz at at least 4.5V. [9] The Arduino's serial port defaults to an asynchronous mode (meaning it does not require an independ clock signal to function) but is capable of other modes, such as synchronous mode, in which an independent signal carries the clock information back and forth. As for the power supply within the Arduino, it itself does not provide any power, but handles routing, regulation, and filtration of power it receives from an external source. [9]

Along the sides of the boards there are four sets of expansion connectors. These contain the digital, analog, power, and other pins that allow for the connection of additional circuitry as well as some add-ons, such as the ultrasonic distance sensor utilized by the CDAR project. The digital and analog pins allow for digital and analog input respectively. But, while the digital pins also allow for digital output, the analog pins do not provide analog output as the Arduino does not support it. Instead, the analog pins support pulse width modulation (PWM) to simulate output by way of manipulating digital pulses and allows for a wide range of analog values.

Greatly adding to the utility of the Arduino is the functionality of installing shields through the expansion connectors. These shields allow the standard board to act as a miniature motherboard that can provide a vast number of expansion capabilities to the standard board.

[1] Atmel is a registered trademark of Atmel Corporation
[2] AVR is a registered trademark of Atmel Corporation

Different shields offer different tools for the Arduino to utilize, such as the Xbee[1] shield that allows for the wireless communication of multiple Arduino boards or the Motor shield that enables manipulation of DC motors. The CDAR project makes use of Wifi and Ethernet shields to allow for communication between boards and a server to transmit collected data.

[1] Xbee is a registered trademark of Digi International, Inc.

Project Aim

The aim of the CDAR project is to provide solutions for two sustainability problems. The first concerns the matter of efficiently collecting distributed recycling within a city, university, or other organization and the second the quantification of recycling programs at a finer level of granularity than is presently taken into account. The idea for this came about from an observation made regarding the present state of recycling collection. Specifically, how collection schedules did not always line up with the degree to which people recycled. Often times there would be a situation in which recycling bins would be overfull and yet collection would not be due until some time later. Similarly, there could be times where it would be time to collect but the bins would be nearly empty. This inefficiency resulted in a waste of resources that did not have to be and thus lead to the creation of the solutions proposed.

The collection problem is tackled by means of CDAR software coupled with an Arduino sporting an ultrasonic distance sensor along with internet connectivity shields. A distributed network of these Arduino units are placed throughout an area within recycling bins and periodically measure the distance from the unit to the bottom of the bin. A smaller distance measurement would indicate a fuller bin. These readings are then uploaded to a database which keeps track of which unit sent the reading and what that reading was. Once enough data has been accumulated predictive analytics can be applied to create predictions of when each bin might next be ready for collection again. With this data a schedule can be devised that details which bins should be visited on which day and plots routes accordingly. Reducing the number of stops will allow for more efficient consumption of resources that would normally be wasted in visiting bins that may not even need emptying. The latter problem is handled by the measurements taken themselves. Current means of tracking recycling collected are reported in large numbers. That is to say, recycling is typically measured in terms of X many tons collected over Y period of time. The data collected from Arduino measurements will be able to detail to the centimeter how much recycling was accumulated over so much time and this will allow for a much more accurate report of how much was collected to a much finer granularity.

Literature Review

Sustainability

Within the realm of modern sustainability a major component is sustainable development. Sustainable development is, as previously stated, "...development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (as defined by the Brundtland Comission) Since this topic became more prominent in the public consciousness various groups have sprung up to offer their own insight into what topics may present problems in regards to generations' needs and how to go about solving them. These differing opinions can be grouped into three major categories; the Institutional Version, the Ideological Version, and the Academic Version of sustainable development. [10]

The Institutional version of sustainable development closely adheres to the Brundtland Commission's definition in that the goal of 'need satisfaction' is key. The three major players of this group, the World Commission on Environment and Development (WCED), the International Institute of Environment and Development (IIED), and the World Business Council for Sustainable Development (WBCSD) agree on this matter. However, they differ on the specifics of the perceived solution. For example, while the IIED feels that rural development through communities is the proper approach, the WBCSD feels that instead business interest through business and industry is what will solve the problem. Their objective within sustainable development will be to maximize the achievement of goals set within the boundaries of their believed heuristics. [10]

In contrast, the Ideological version is dominated by such schools of thought as Eco-theology, Eco-feminism, and Eco-socialism. Each identifies a different goal that can be obtained via a movement championing their school of thought. Eco-socialism, for example, arose during the 1970s out of the idea that sustainable capitalist development could not happen, and thus they feel the root of environmental problems are capitalist in nature, for example, and that changing the modes of production can solve issues. Eco-theology, on the other hand, feels there is a wealth of information available within religious traditions that could help to alleviate environmental woes. By allowing religious virtue to shape human lives, they feel, human relation to nature will attain proper balance for sustainability. [10]

Lastly, the Academic version of sustainable development is reflected by the economist, ecologist, and sociologist conceptualizations of what problems exist. Each of these fields seeks to solve their perceived environmental issues by means of applying their particular study to find a solution. In one case, the economic school feels that the environment is undervalued and by applying various valuation techniques it can be determined how valuable the environment is. This serves as an indicator of what level of environmental protection society should adopt. [11] Meanwhile, the ecological field feels that nature on its own is a sustainable system and human dependability on it is the root cause of problems. Their solution, then, is to "...replace anthropocentric hierarchies with biocentric egalitarianism." [10]

Cyber-physical Systems

Modern applications of CPSs feature, similar to the goal of the CDAR project, a distributed network of computational elements of a system interfacing with physical input and output then using collected data to meet some end. Since 2006, the National Science Foundation (NSF) has awarded large grants to fund research projects in the field of CPSs. [12] This research covers such applications as design, implementation, real-world applications, and theoretical foundations. Despite the growing awareness of the significance of advancements within the field, it is still fairly young.

Being a new field leaves CPSs with much room to grow, as it is thought that "the foundational challenges of CPSs require top-to-bottom rethinking of computation." [13] For example, one such area under development is that of memory management with predictability.

The problem that arises is that while automatic memory management helps with programmer productivity and software reliability, it comes at the expense of timing predictability. One possible remedy to this problem is an exploration of bounded pause-time garbage collection, which researchers seek to implement (in this case in regards to Java) as a true real-time garbage collector integrated with the scheduling system utilizing non-copying mark-sweep and copying collection (in case of fragmentation). [14] Another example of research deals with concurrent components and how component software technologies do not mesh well with concurrent real-time computation. [13] A proposed solution to this issue is a new design structure called *Actor-oriented design* that seeks to “emphasize concurrency and communication between components.” Here, components called *actors* are the focus of design rather than objects as in object-oriented design. [15]

Arduino

As the Arduino platform began to pick up steam with its rising popularity, several other models of boards began to enter production to meet the needs of different projects and hardware requirements. While main boards such as the Uno and Mega can be used for a myriad of projects, some boards were introduced to meet more specialized specifications.

One such board, the LilyPad Arduino, distinguishes itself from other boards by being designed with being utilized in wearable and e-textile projects in mind. It stands apart from typical rectangular Arduino units with its circular shape and its support for being sewn to fabric or power supplies with conductive thread. This functionality comes at a cost of hardware performance in comparison to the Uno, however. The LilyPad only boasts roughly half the memory and clock speed of the standard board. On the positive end of this, the LilyPad requires less power to function. [16]

The Arduino Due, on the otherhand, stands opposite to the LilyPad. This board is the first Arduino unit to be based on a 32-bit ARM core microcontroller and as such features dramatically higher memory allowances and clock speeds. These of course come with higher power requirements, however. [17] A more powerful board allows for more intensive computation of embedded projects such as supporting more hardware attachments than perhaps the Uno or being able to process instructions faster.

Project Discussion

As was mentioned previously, the two goals of this project are efficiently collecting and managing distributed recycling within a city or other organization and the quantification of recycling programs at a finer level of granularity than is presently taken into account. Both of these issues are tackled by way of the CDAR project's application of an Arduino microcontroller, hardware attachments, and application developed to control and manage the device and the data collected. These items will be discussed at length along with discussion of future steps to be taken.

At the core of the project is the Arduino, specifically the Arduino Uno. This is the lightweight version of the platform, as opposed to the Arduino Mega which features more powerful hardware along with a larger physical size. The Uno is driven by an ATmega328 microcontroller chip, which boasts 32 kilobytes (KB) of flash memory, 2KB of static random-access memory (SRAM), and 1KB of electrically erasable programmable read-only memory.

Flash memory describes an electronic, non-volatile storage that can be programmed and electronically erased. This allows the Arduino to store information even when it is not being powered. SRAM is a type of memory that grants the Arduino memory to utilize while it is performing operations. However, it still needs the flash memory as once it loses external power any data that was being stored within this memory is deleted. SRAM is faster than its counterpart, dynamic random-access memory (DRAM), and does not have the refresh requirement that DRAM does. Random-access memory in general utilizes transistors and capacitors to manipulate and store charges to represent the bits that comprise information. With DRAM, whatever bits are stored will be periodically read and then rewritten without any change in order to preserve the data. However, DRAM is more efficient per bit than SRAM by way of only needing one capacitor and transistor per bit. Finally EEPROM, similar to flash memory, is another form of non-volatile memory (that is, the data it contains is not lost upon power loss) but it distinguishes itself from flash by being erasable in small blocks of memory as opposed to the larger blocks used by flash.

The Uno has a standard operating voltage of 5V (DC) and a recommended input voltage of 7 to 12V. Internal resistors located within the board reduce incoming voltages to acceptable levels, however, a voltage outside of these bounds runs the risk of damaging the board.

Pictured: An Arduino Uno next to a quarter for a scale reference

Each of the 12 input/output (I/O) pins located along the side of the board has a direct current (DC) draw of 40mA. These are the pins that allow for attachment to various peripherals such as the acoustic distance sensor and WiFi shield being utilized. The board has a standard clock speed of 16MHz, which translates to 16 million cycles per second, with a clock cycle being the frequency of a sine wave produced periodically that is used to determine a central processing unit (CPU)'s speed.[18]

Driven by the Arduino Uno are the two components responsible for the collection and transferral of the data being collected: the WiFi shield and the PING)))[1] ultrasonic distance sensor from Parallax, Inc. These components rely on the Arduino for power and direction and are connected to the board via its I/O pins.

The Ping))) sensor works by interfacing with three of the Arduino's pins, any one digital I/O pin (specified in the user's code) for the signal (SIG), a 5V pin for power, and a ground (GND) to complete a circuit to it. It works by sending a pulse of ultrasound then listening for the return echo (provided it reaches between its 2cm to 3m range). The Arduino triggers this by sending a high pulse (a 5V signal) to the SIG pin. Once the echo is received the time it took for the pulse to return, in microseconds, is determined.[19]

Pictured: A Ping))) distance sensor from Parallax [20]

The Arduino code that handles this is called a 'sketch', and it works by containing two crucial functions that run whenever the Arduino is powered on. The first is a setup function that initializes any values or other functions the unit will use. The second is a loop and this is where the main body of code goes. Any code within this loop function will run endlessly until the

[1] PING))) and Parallax are trademarks of Parallax Inc.

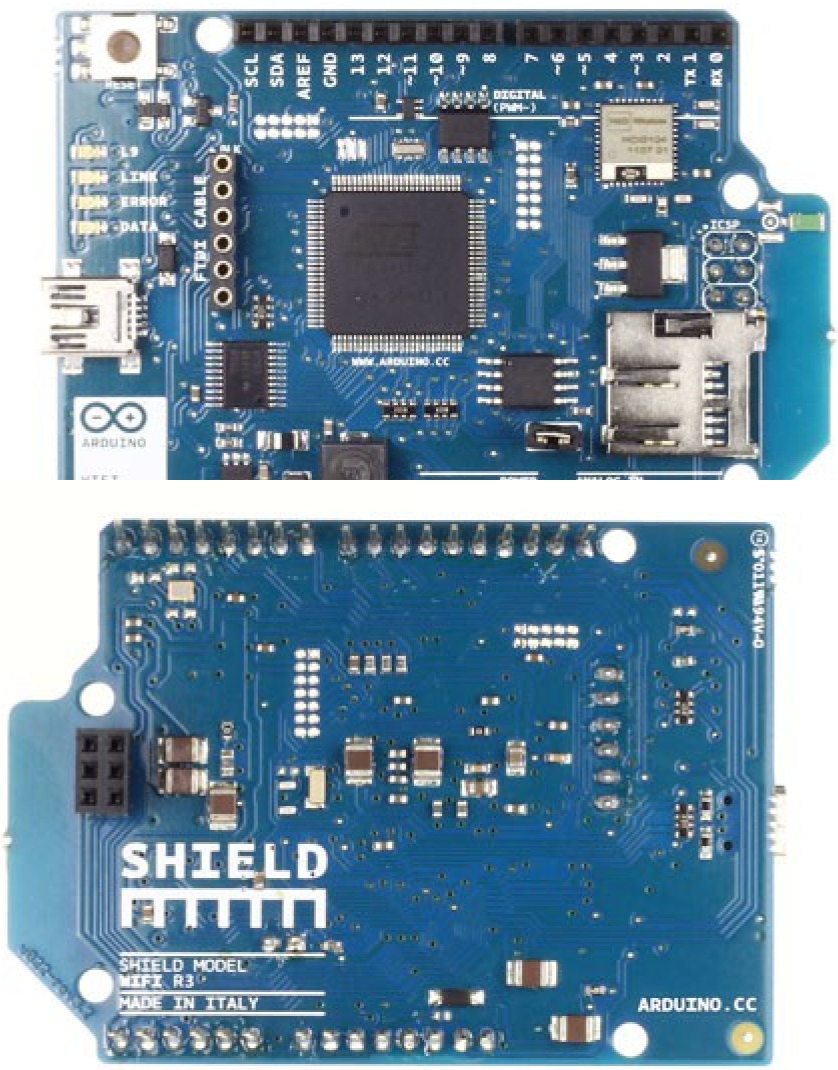
Arduino loses power or is stopped by some external entity. By factoring in the speed of sound it is possible to calculate a distance from the echo measurement to the centimeter. With a distance measurement in hand, it is possible to determine how full a recycling bin is by comparing the measurement to the known volume of a bin. For example, if a bin is 2ft by 2ft by 3ft for a volume of $12ft^3$ and a distance sensor reading only returns 1ft, then we know that only $4ft^3$, or 33% of the bin's volume is full.

That being said, in recent test runs of the unit within an actual recycling bin, some anomalous data has been found. While readings between the device and the floor of the bin were obtained and showed a steady increase as recycling was collected it appears as though the motion caused when discarding material can cause some irregularity in the measurement. This could be due to refuse not falling neatly to the bottom of the bin or perhaps movement of the bag getting in the way of the device's sensor, causing an erroneous reading. Initial ideas into solving this include taking steps to further secure the garbage bag within the bin to prevent its movement or discarding spikes in readings that do not fit, as those are most likely to be caused by disturbance. In any case, further exploration will be needed into possible solutions to this problem in future work on the project.

This data is communicated to a server through a WiFi shield. A shield is a specific type of Arduino attachment that interfaces with all of the Arduino's pins, giving the board access to the shield's functionality while the shield itself providing a means to still utilize the Arduino's pins by providing its own pins that connect to them. The shield has an operating voltage of 5V that it receives from the Arduino and communicates with it via a serial peripheral interface (SPI) bus. This bus is a type of synchronous serial data link that allows for communication back and forth between the Arduino and the shield. The shield provides a connection of the 802.11b/g, a version of the WiFi protocol enacted by the Institute of Electrical and Electronics Engineers (IEEE), standard, and provides functionality for the WEP and WPA2 Personal encryption types.

WEP stands for Wired Equivalent Privacy and is an encryption protocol that was intended to replicate

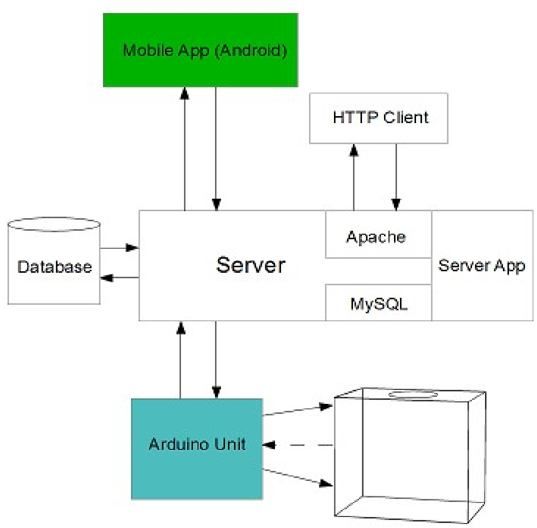
the strength of wired internet privacy. However, it is typically discarded in favor of WPA2 (Wifi Protected Access II), which is much more secure by utilizing stronger encryption. [21]



Pictured: An Arduino WiFi shield [22] [23]

By means of the Arduino WiFi library of functions, the shield can take advantage of both User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), which the CDAR project is making use of to send data measurements. TCP is typically preferred as it provides functionality for checking that no data was lost in transfer and that all of that data was received during a transfer as opposed to UDP's method of simply sending data to a recipient with no error-checking whatsoever.

Once a measurement is picked up by the distance sensor and transferred by the WiFi shield, it is sent to a server. The CDAR project is currently utilizing a LAMP stack (a Linux machine protocol) hosted in the cloud provided by Amazon's Elastic Compute Cloud (EC2) platform for that purpose. A LAMP stack is a bundle of software packaged together as their combined functionality creates a general purpose web server. The acronym refers to the first letters of each piece of software contained in the bundle. These are Linux, Apache HTTP Server, MySQL, and PHP.



Pictured: a model of the CDAR architectured

Linux is an open source operating system (OS) meaning the source code behind it is freely available to anyone who would wish to see or alter it. Many different flavors of the OS exist but Amazon uses their own distribution based on Fedora, another type of the Linux OS. Linux is not necessarily required for such a bundle, as WAMPs and MAMPs (Window and Mac AMP stacks) exist, but Linux's open source nature is a large boon for developers with its free cost and flexibility.

Apache is a web server program that is used for such things as delivering web pages to web clients by way of Hypertext Transfer Protocol (HTTP), providing support for server-side programming languages, and authentication schemes. The functionality necessary to run a web server is provided by Apache. MySQL is a structured query language (SQL) database management system (DBMS) that provides a LAMP stack platform with the means to host and manage a database through data tables, where the database's information is stored. Lastly, PHP is the programming language used to program server-side application software used by the platform. While PHP is common, Perl and Python can be used as well.

These components form the basis of the project; the Arduino and its hardware attachments collecting the data and feeding said information to the database on the server. In addition to these, there are in development both an Android[1] application and a website that will allow for monitoring of the network of bins and to what degree they are full. Also being explored is the issue of external power. Initially it was thought that batteries would suffice in powering the unit but recent tests with both 9V and clustered AA batteries showed that neither source was able to power the unit for even 24 hours.

With one unit set up and recording data at the time of this writing, the next step is to scale the project's scope up to more units to form a network over a distributed recycling as was specified in the original project goal. As these units collect more and more data, the next step

[1] Android is a trademark of Google Inc.

will be to devise an algorithm that incorporates predictive analytics in order to create a forecast of when any given bin within the network might next be full. With this algorithm in hand, a schedule can be devised detailing which bins to visit for a route each day based on which bins should be full. This data will also have been measured at the finer level allowed by the sensing hardware and will provide insight into changes in trends of recycling to the centimeter, that is to say, a much finer granularity than is presently taken into account.

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