Report as of FY2008 for 2008DC97B: "Application of Spaciotemporal Informatics to Water Quality"

Publications

Project 2008DC97B has resulted in no reported publications as of FY2008.

Report Follows

Application of Spatiotemporal Informatics to Water Quality (Phase I)

Progress Report

UNIVERSITY OF THE DISTRICT OF COLUMBIA

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Content

Abstract

Recent developments and innovations in spatiotemporal informatics (storage, update, and retrieval of continuously changing data) and relevant sensor technologies can provide exciting opportunities and innovations in urban water resource management and decision making applications. For example, for the implementation of the Long Term Control Plan (LTCP) that addresses the combined sewer overflows and storm water discharges problems in the District of Columbia, such emerging technology and developments can significantly enhance and improve the monitoring and decision making processes.

The objective of this multidisciplinary (Civil Engineering and Computer Science and Information Technology) project is to devise a highly efficient and effective technology for stormwater quantity and quality monitoring by taking advantage of much emerging advances in spatiotemporal informatics and relevant sensor technologies.

The benefits of the project include the following: (1) highly cost-efficient and continuous monitoring of the runoff quantity and quality; (2) data and tools for real-time analysis and sharing of raw runoff data for better emergency and maintenance decisions; (3) lab and field training, education, and research.

Upon completion, this proposed project will benefit the District of Columbia in the development and implementation of a watershed wide innovative stormwater quantity and quality water quality monitoring system to measure flow and water quality parameters at the combined and separated sewer outfalls.

In the Phase I of the project, a competitive proposal was developed and submitted to NSF for extramural funding. The peer review identified as one of the innovative proposal with intellectual merit, however recommended that the proposal should include more preliminary experimentation. The Phase II of the proposal includes the laboratory experimentations and the development of an improved proposal with a submission to the NSF Sensor Network program in year 2009.

1.0 Introduction

Over the last couple of decades, it has been recognized that urban stormwater pollution is a large contributor to water quality problems of many receiving waters, as runoff transports a wide spectrum of pollutants to local receiving waters and as their cumulative magnitude is large [20].

The pollutants in urban runoff include visible matter, suspended solids, oxygen demanding materials, nutrients, pathogenic microorganisms and toxicants such as heavy metals, pesticides and hydrocarbons. These pollutants impose considerable physical, chemical, and biological stresses on the receiving waters that affect aquatic life and human health [12] and impair the designated uses of water resources. Typical urban stormwater-runoff-related receiving water quality problems include the degradation of aquatic habitats, degradation in water quality during and after wet weather events (e.g., rainfall and snowmelt), beach closures, and accelerated rates of eutrophication in lakes and estuaries, and thermal pollution [20]. These problems have been prevalent in most receiving water systems in the vicinity of urban or urbanizing areas.

In the District of Columbia, *combined sewer overflows* (CSOs) and *stormwater discharges* contribute significant pollution to the Anacostia and Potomac Rivers and Rock Creek, especially during wet-weather periods. These runoffs can adversely impact the quality of the receiving waters particularly Chesapeake Bay. The Anacostia River, a tributary of the Potomac River has been significantly impacted pollution, principally (Biannual Report, October 2005, WASA). To address these problems, District of Columbia is implementing a Long Term Control Plan (LTCP) which, over the next 20 years, will reduce the overall volume of overflow into waterways by 96 percent and the plan will cost approximately $2 billion dollars.

This proposed project shall devise and verify such an efficient technology that can continuously monitor and measure the runoff quantity and quality in real-time.

To assist the decision-makers in implementing the LTCP, a real-time and continuous assessment of the severity of the runoff pollution in each sewer outfall (and the associated sub-catchment within the watershed) is necessary. The severity of the pollution governs the identification and prioritization of problems as well as the corresponding resource allocation and response decisions in LTCP. Hence, a continuous measurement of the quantity and quality of the runoffs is a key issue.

However, the management difficulties and high costs of any conventional human-involved data collection approach may pose major challenges. In the application's backend, we see a timely and critical demand for an innovative and cost-efficient approach to continuous and real-time measurements of the runoff quantity and quality.

This demand and effective environmental regulations, such as Total Maximum Daily Load (TMDL), give rise to the opportunities for the development of an effective stormwater and wastewater quality monitoring technology. The objective of this multidisciplinary (Civil Engineering and Computer Science and Information Technology) project is to devise such a monitoring technology by taking advantage of much emerging advances in spatiotemporal informatics and relevant technologies and to verify this deliverable technology.

2.0 Motivation and Research Objectives

Although various sensor technologies have been developed for water flow measuring, there is a marked lack of cost-efficient, continuous, real-time, long-term, autonomous, and scalable monitoring solutions for urban runoffs found at the discharge outfalls. Especially, manual methods and other sensor solutions require human labor for operation and maintenance, often incurring cumulative health risks to the field workers for directly accessing the pollution discharge points. This represents non-continuous and short-term/ad hoc monitoring solutions, which degrade the overall reliability and responsiveness of the society's water resource management and research.

To assist the decision-makers in realizing a long-term control plan (LTCP), a real-time, continuous, and cumulative assessment of pollution at sewer outfalls (and the associated sub-catchments within the watershed) is required. The severity of the pollution governs the identification and prioritization of problems as well as the corresponding resource allocation and response decisions in LTCP. However, the management difficulties and high costs of any conventional human-involved data acquisition approach pose major challenges.

Current environmental regulations, such as Total Maximum Daily Load (TMDL), require that the regulatory authorities must monitor receiving water bodies, such as streams, rivers, and lakes, for pollutant loads on a regular basis. This makes the motive of the project even more pronounced.

The project team has initiated this multidisciplinary project (comprising civil engineering, electrical engineering, and computer science expertise) in order to investigate the following envisions:

- A wireless, autonomous, and tiny sensor-computer at each discharge/outfall location: the development of a cost-efficient (in terms of installation, operation, maintenance, and geospatial scalability) and tiny sensor-computer technology for autonomous, continuous, long-term, and real-time monitoring of urban runoffs and CSOs (Combined Sewer Overflows).

- An on-line information server – the development of a central on-line information server that can utilize such sensor-computer technology, that can continuously receive, record, and report runoffs with minimal human support, and that can actively alert human as necessary in real-time.

This multidisciplinary project is, by nature, explorative and includes untested and transformative elements mainly as innovative applications and study of emerging sensor-computer (small and highly programmable sensor objects) technologies and relevant informatics.

Long-Term Objective: *Devise and verify a novel sensor-information system that can continuously monitor, record, and analyze urban wastewater and stormwater at sewer outfalls in a cost-efficient, autonomous, and highly scalable manner for long-term periods.*

The scope of the current Phase I of the project is to experiment with newly developed Sun Small Programmable Object Technology (SPOT) computers and sensor technology to develop stormwater quantity and quality measurement techniques. The project will be implemented in three steps –

(I) analysis of the SPOT and testing of programming ability to use as a monitoring device for water and wastewater;

(II) development of a lab-based experimentation to verify the use of the SPOT to measure velocity and discharge rate of water;

(III) development of a extramural funding for the installation of the equipment in the sewer outfall of the Rock Creek to measure water quantity and quality parameters. Few water quality parameters, such as water temperature and solid pollutants, will be tested. Based on the success of this project, more water quality parameters will be added on the availability of sensors.

3.0 Related Solutions

Flow monitoring for runoffs at sewer outfalls (discharge pipes along the receiving water) is complex because of the intermittent nature of the flow. The flow measurement techniques vary greatly in complexity, cost, and accuracy. The methods of runoff discharge monitoring technology can be classified, in a broad sense, into either direct or indirect.

A direct method measures the quantity (volume or weight) of the flow during a given time interval for closed conduits flow or pressurized flow. For gravity flow, the principle of open channel flow is typically used. The flow rate is computed by measuring the velocity of flow and by computing the area of flow. Hydraulic engineers have developed some equations -- given a depth of flow, there is a unique and predictable flow velocity (and flow rate) of water in the pipe, which can be derived from Manning's Equation. Another standard pipe curve is known as the Colebrook-White Pipe Curve [10].

Indirect methods measure pressure changes for closed conduits flow (or some other variable), which is directly related to the rate of flow. Examples include venturi meters, orifices, etc. Weirs are devices that employ indirect means to obtain partial flow rates. Some other types of indirect methods employ electro-magnetic flow meter device, which operates on a principle that a voltage is generated when a conductor moves in a magnetic field.

Among the simplest methods are the conventional methods that involve manual measurements of runoff quantity and quality (using various measuring tools, such as poles, bottle board and chalking, and dye testing). However, the manual methods rely extensively on labor-intensive field efforts during storm events and do not provide an accurate, continuous flow record [11].

Recently developed techniques employ flow devices, such as weirs, flumes, and orifice plates. The accuracy of flow calculations depends on the reliability of depth sensing equipments, since a small error in depth measurement can result in a large error in flow rate calculations. Some typical depth–sensing devices include the following:

1. Ultrasonic Flow Meters – employ a technique to measure the difference in travel time for a sound wave traveling upstream and downstream between two measuring stations. The difference in travel time is proportional to flow velocity. The other type of operation is based on Doppler Effect which is based on capturing the differential frequency (Doppler shift) during the

projection of ultrasonic beam into fluid. The measured frequency difference is related to the flow velocity.

2. Ultrasonic Sensors – are typically mounted above the flow. The depth is computed based on the time the reflected signal returns to the sensor. The depth measurements can be affected by the suspended solids of the runoff.

3. Pressure Sensors – sense the pressure of water above them. They are used along with a flow monitor that converts pressure value to a depth measurement and are hard to use at an open end of a pipe, such as a sewer outfall.

4. Bubble Sensors – emit a continuous stream of fine bubbles. A pressure transducer senses resistance to bubble formation, converting it to a depth measurement value. The bubble tube are often clogged, requiring frequent calibration

5. Electro-magnetic Flow Meters – operate on a principle that a voltage is generated when a conductor moves in a magnetic field.

4.0 Analysis of SPOT

4.1 Introduction to SPOT

SPOT (Small Programmable Object Technology) device is a HP product having 180 MHz 32 bit core, 512k RAM, 4Mb Flash drive, 2.4 GHz IEEE 802.15.4 radio, USB interface, light and temperature sensors, 2G/6G 3-axis accelerometer, 8 tri-color LEDs, 6 analog inputs, 2 switches, 5 general purpose I/O pins, 4 high current output pins, fully programmable operating system. The size is slightly bigger than the matchbox (41 x 23 x 70 mm) and it weights only 54 grams. This device is a new generation portable computing experimental platform designed in Sun labs. It is called Sun SPOT device.

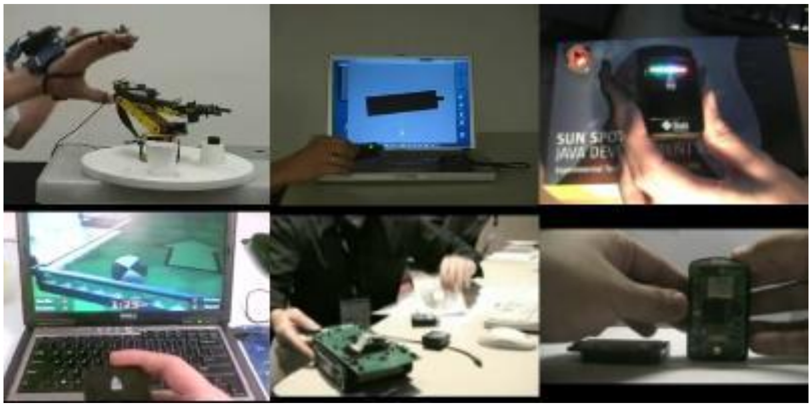


Figure 4.1 : SPOT System

Such advantages of the Sun SPOT as small size, wireless communication, and battery power make it extremely useful as an experimental platform. “Sun SPOT devices include a flexible hardware platform as well as the software and tools to make it easy to innovate, experiment, and prototype whatever a developer can imagine.”(Sun SPOT FAQ) Sun Microsystems made the SPOT development available on almost every widely used operating system for both PC and Apple (Windows XP, Windows Vista, Macintosh OS X 10.4, Linux (Fedora Core 5, SuSE 10.1 and Ubuntu 6.06), and Solaris x86) There are more than 400 classes documented in Sun SPOT JavaDoc. Dun DSK provides us with more than 300 high level classes to access SPOT input and output hardware.

The area of Sun SPOT usage is amazingly wide. Some of them are(Figure 1):

- Education
- Medical Applications
- Industrial Research
- Government and Military Applications
- Robotics

The list can be continued on and on. The latest new from Sun Microsystems is that the SPOT project is going fully open source which opens even more opportunities for the developers. More information about SPOT projects can be found at www.sunspotworld.com/about/vision.php.

4.2 SPOT Package

The Sun SPOT package includes two Free-range Sun SPOTs (equipped with a battery), a base station, Software Development Kit CD, and USB cable. (Figure 4.2). The base station is used to connect to computer and wirelessly operate free-range device, though the free-range SPOT can be used as a base station as well. The SDK CD has detailed installation manual for both Linux and Windows. Each SPOT device has its' own MAC address which is being used as a login when accessing Sun SDK updates. The MAC addresses in my case were:

Figure 4.2

- 0014.4F01.000.0734 (freelance device)
- 0014.4F01.000.070f (freelance device)
- 0014.4F01.000.0c9b (base device)

4.3 SPOT Development process

Sun SPOT SDK is a complex set of tools that include Java compiler Sun made the SPOT software development very simple as the programmers can use standard Java tools such as NetBeans or Eclipse. Currently, NetBeans is the preferable development tool, due to its' tight integration with the SPOT devices. The latest version of SDK is 4.0 (Blue).

4.4 SPOT Analysis

The project is subdivided into three major parts:

- Programming
- Analysis
- Laboratory testing.

The first part included development of software to sense and record several sensor readings such as 3-dimensional position and velocity, temperature, and light values. Java Telemetry program was used as a base. It was modified to read light and temperature values, sense position instead of acceleration, calculate 3-dimensional velocity of object and store sensed values in a file. This part is mainly finished, though there is always a lot of space for the upgrades and improvements.

The second part is much more challenging as it involves the development of a formula (or variety of formulas with different precisions for various conditions) to approximate the amount of waste water based on the sensed values. This stage of the project is in active development and elaboration. Several approaches are used to accomplish the goal. Some results are already available in the attachment and ready to be tested in the lab.

The third part is the lab testing. It would require construction of the tube in the lab and testing the formulas in the real-world conditions. The implementation of the laboratory testing device is out of scope of this paper; though the testing results would be published as they would become available.

5.0 Project Development Planning & Analysis

Our proposed approach is based on a newly developed Small Programmable Object Technology (SPOT). This tiny sensor-computer platform consists of stacked three layers: Li-Po battery, sensor board, and tiny computer with a CPU (Java programmable), timer (AT91 timer for measuring time elapses), USB, power switch, and memory. The sensor board includes the following: 3-dimensional accelerometer (LIS3L02AQ), temperature sensor, light sensor, eight LEDs, two switches, five general-purpose I/O pins, and four high current output pins. Figure 1 shows SPOT devices in our laboratory.

The proposed methods of this project are as follows:

1. Instrumentation: Encase a SPOT computer inside a sealed sphere and tether it inside each target sewer outfall pipe as shown in Figure 5.2 (a lab-made pipe and artificial water input will be tested before actual field tests; before the field tests, the project will select target pipes in the Rock Creek region).

2. Runoff logging: The 3D acceleration data stream (swing motion sequence) from this sensor represents the runoff flow over time. The project will also try to see if some jerky and/or lateral motions caused by physical debris or sudden water bursts are usable for additional information. The project will also investigate possible uses of the temperature and light sensor of the SPOT for additional information. Connecting more sensors to the I/O port of the SPOT will be considered based on the results of this project.

3. Filtering and Aggregation: The programmable SPOT can filter-out insignificant events for optimal use of storage and communication bandwidth and provide representative summary data (pre-processing).

4. Students involved in the project will drive or walk by the sphere with a laptop computer equipped with a SPOT base station on a regular basis (again, lab tests will precede this field test). All logged data will be automatically transmitted to the laptop’s hard disk. Then, the acquired data will be transmitted to the information server (running on the project server computers located in our laboratories) both manually and via WAN/Cell network interface to the Internet. The server will also run the project’s web site for the academic dissemination of the data, research, and findings.

5. The project team will install a solar panel at each site and connect the charging mini USB cable to the SPOT. (SPOT can run on its battery for some days, just like cell phones; charging the battery takes a small number of hours.) This will eliminate the need for manually opening the sphere to replace or charge the battery.

: Wireless (radio) communication

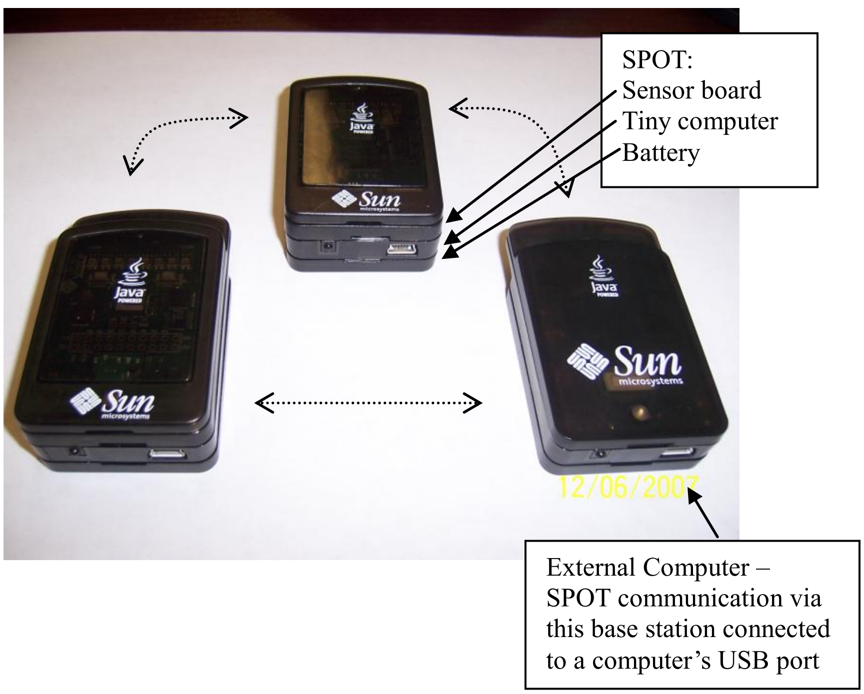
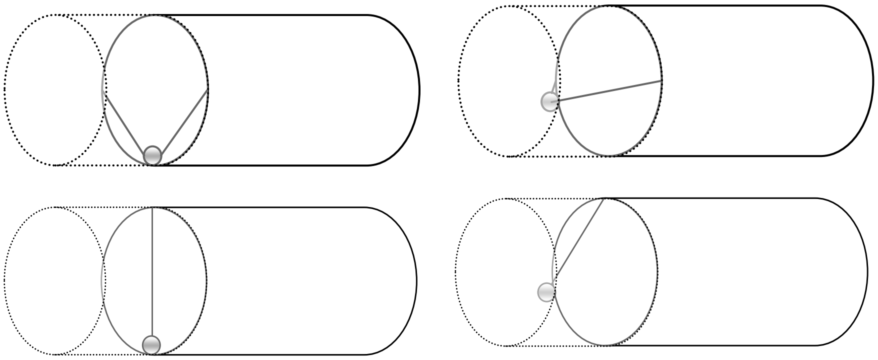
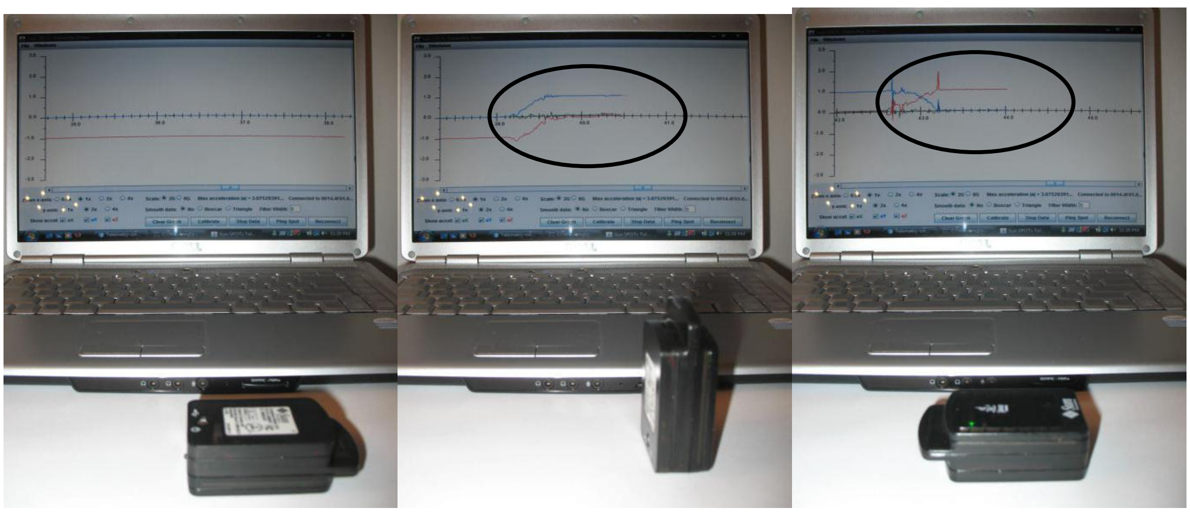


Figure 5.1. SPOT Computer: The physical dimensions in mm are 71mm×42.40mm×18mm. This tiny computer can run any Java program that accesses the sensor board.



(a)

180 degree turn on the YZ plane in two steps



Acceleration is measured in gravities (g)	Before	After		180 degree turn
		Step 1: 90°	Step 2: 180°	
Green X-axis	0	0	0	
Blue Y-axis	0	1g	0	
Red Z-axis	-1g	0	1g	

(b)

Figure 5.2. (a) Sphere's motion inside an outfall pipe (two of the possible configurations); (b) A sample of many accelerometer tests conducted in our lab

5.2 Technical Approaches

<u>Calculation of the depth of flow in a pipe :</u>

The SPOT device will be sealed inside a sphere made of appropriate material such as tin, or plastic and attached on the top of the pipe using one or two light solid bars or strings (alternative configurations will be tested). The sphere should provide enough buoyancy to float it on the surface of water. The device can compute the inclination, or tilt (θ in Figure 5.3), of an axis with respect to the total acceleration the device is experiencing [13]. In our application, the tilt is measured with respect to the gravity flow within the pipe. When there is no water in the pipe, the sphere is at the bottom and the tilt is zero degree (θ=0°). When water flows, the sphere will float on the water and water level or height (h) is calculated using the tilt as follows (the buoyancy factor will be added after lab tests):

$$\theta' = \pi / 2 - \theta,$$

$$\sin\theta' = \frac{d-h}{d},$$

$$h = d - d\sin\theta' = d(1-\sin\theta'), \text{ where } d \text{ is the diameter of the pipe.}$$

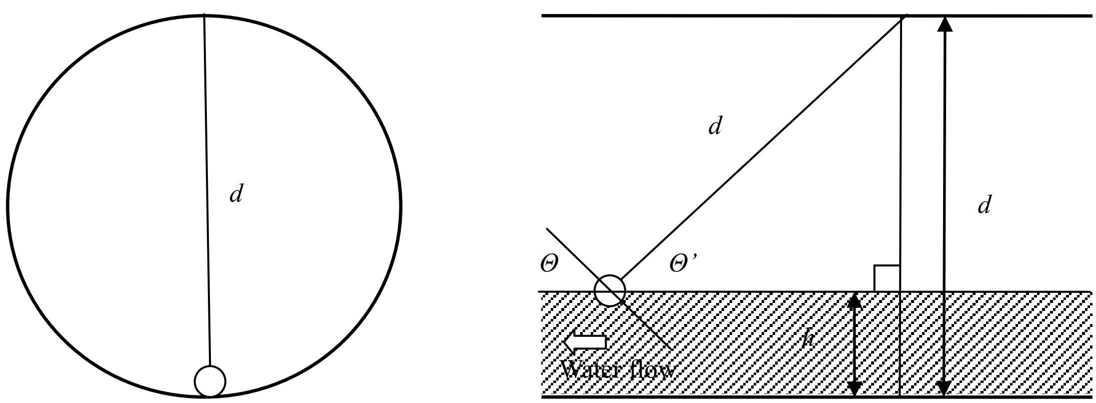


Figure 5.3. Calculation of water height using SPOT

<u>Calculation of the flow rate, given a depth :</u>

Given a depth of flow (h), the flow rate will be computed based on commonly used hydraulic principles. The flow rate (Q) will be computed from the continuity equation (conservation of mass principle) by the product of the water velocity (V) and the area of water flow (A), i.e., $Q = A \cdot V$. The partial flow area in a circular pipe can be calculated as follows and as depicted in Figure 4.

$$A = \frac{\beta}{360}\frac{\pi D^2}{4} - \sqrt{2rh - h^2}(r-h)$$

, which is the area of the arc with angle β subtracted by the area of the isosceles triangle. The velocity of water can be computed by using Manning’s formula which is as follows:

$$V = \frac{1}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$$

, where n is Manning’s roughness coefficient, R is hydraulic radius (flow area A divided by wetted perimeter p), and S is the slope of the pipe.

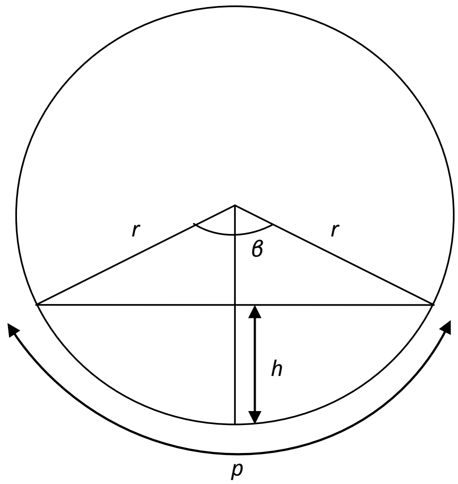


Figure 5.4. Calculation of area of water flow

Smart memory management:

SPOT is able to read samples at the maximum rate of 320Hz. SPOT will continuously monitor and record the water level (*h*), water temperature (*t*), and water clarity (*c*) with a predefined time interval *I*. Due to SPOT's limited memory capacity (4 Mbytes of flash memory [16]), it is important to know SPOT's maximum data acquisition period between two consecutive batch transmissions. First, suppose that SPOT is always collecting the data with a constant interval *I* regardless of water flow. This can be the worst case – maximum amount of data collected. For example, suppose that a sample of 5 bytes of data is collected at every certain time interval (2 bytes of real time data plus *h, t, c*, each one byte). Then the total collected data for a week amounts approximately 3 Mbytes of storage when the sampling interval is one second. SPOT's 4 Mbytes of memory could be enough for a week-long data acquisition without any data transmission.

Then there can be various techniques to extend this data acquisition period. One can store sample values only when they vary over a certain difference Δ. SPOT senses sample values at the beginning of every interval. However, if water level does not change much, it does not need to store the stimuli values until the change exceeds Δ. This approach can save significant amount of memory space in our application because 1) there would be no water flow under normal weather and 2) even in the presence of water flow, water level would not change abruptly in most time. Thus, the small amount of memory can possibly be sufficient to hold sample data for a far longer extended time period than a week, which will be investigated in this project.

Smart power management:

Without any external power, the SPOT battery can run up to 6-7 hours on the full power mode with wireless communication and LED on. Providing external power source is critical in the proposed long-term and continuous monitoring application. We propose a solar panel for the purpose due to its cost efficiency and reliability. However, even solar panel cannot provide sufficient power during night and cloudy day, especially during wet events. SPOT can be operated in three different modes to save its battery power, *Run, Idle,* and *Deep-sleep* mode [16]. In Run mode, SPOT performs basic operations with all processors and wireless communication running, just for 6-7 hours. Idle mode shuts off some unused circuits and the radio, which makes SPOT run three to five times longer than in Run mode. Deep-sleep mode shuts down all circuits except the minimal circuits to resume the operation when it is awakened. This mode consumes only 1/3000 – 1/4000 of the power comparing to Run mode. We can program SPOT to sleep most time except when it actually collects data and communicates with server. By alternating Run and Deep-sleep mode based on the smart memory management and data sampling algorithms, SPOT can operate for weeks or a month without any external power. The project will investigate this smart power management.

Signal Processing :

In contrast to other sensors, SPOT contains a complete computer with built-in signal-processing and filtering functions that are further programmable. According to the PI's meeting with Sun Lab Scientists in 2006, the Kalman filter is worth a consideration in any motion/ trajectory estimation applications using SPOTs. In order to provide constantly accurate and continuously updated information about the position and velocity of the SPOT sphere given only a sequence of observations each of which can possibly includes some error, an additional digital filter algorithms, such as the Kalman filter, will be tested on top of SPOT's signal-processing functions. This will also help us filter out the sideway movements, fluctuations, and jerky motions of the sphere in the pipe.

The final algorithms will be adjusted in the lab and adopted and tested in a field scale experimentation set-up for optimal use of storage and communication bandwidth. The developed filters and other signal-processing/communication algorithms [5-9, 18] will mitigate inferences and further enhance the accuracy and reliability of the information.

Central Database Server

The project will develop a standard SQL/Relational database server using MySQL system to store, update, and retrieve remote sensor data at the central host server. The data transmission from sensors to the host will be accomplished via cellular network and the Internet. The remote database access programming will be based on Java's MySQL database connection library, a widely used and easy-to-use open database access toolkit on the field computer (laptop). The field computer paired with the sensor sphere will enable us to reprogram the sensors remotely without actually visiting the site.

The project's web site will be running on the data server machine hosting the database. The web site will academically disseminate project information, collected data, and research findings.

This permanent data store will bear innovations in water resource decision support applications and will help us develop significant research developing extensive research and iterative enhancements.

Lab and Field Experiments:

The project will test, enhance, and verify the proposed instrumentation both in a laboratory and in the field. The laboratory experiments and research will be performed in our lab (Bldg. 42, Room 111) at the University of the District of Columbia. The experiments will be conducted in a 1-foot diameter tilting pipe. In the first stage, the capsule of SPOT device will be designed with appropriate capsule material (plastic or tin), cushion material, and connection materials and mechanisms. Our experiments will verify their applicability. In the second stage, the instrumentation will be tested for several flow rates and associated velocities. The flow rates calculated by the proposed sphere solution will be compared with the actual flow rates (as shown in Figure 5, it is a closed circuit) as well as other existing technologies including flow meter and velocity meter.

The laboratory results will be further verified in the field. Two sewer outfalls along Rock Creek, which is an urban stream passing near our lab in Washington, DC, will be selected. Generally, these pipes experience overflows when there is a rainfall of more than half an inch in the watershed. The instrumentation will be set up at the sewer outfalls by securing properly such that severe storms will not cause the instrument blow away. The data will be acquired for several storm events. The SPOT data will be compared with the data obtained from the parallel measurements employing existing technologies.

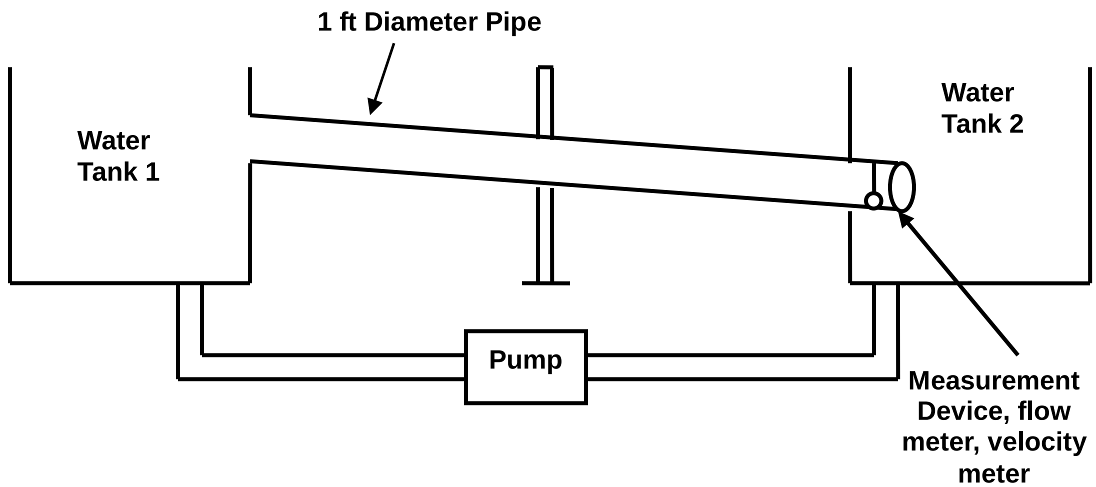


Figure 5. 5. Schematic Representation of Laboratory Experiments

6.0 Acknowledgements

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