Mobile Phone Based Drifting Lagrangian Flow Sensors

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***Abstract*—Mobile phone based drifters offer distinct advantages over those using custom electronic circuit boards. They leverage the inexpensive and modern hardware provided by the mobile phone market to supply water resource scientists with a new solution to sensing water resources. Mobile phone based drifters strategically address *in situ* sensing applications in order to focus on the large scale use of mobile phones dealing with communications, software, hardware, and system reliability. We have demonstrated that a simple design of a drifter built around an Android phone robustly survives many hours of experimental usage. In addition to the positioning capabilities of the phone via GPS, we also use the accelerometer of the phone to filter out samples when the drifter is in storage. The success of these drifters as passive mobile phone sensors has also led us to develop motorized mobile phone drifters.**

I. Introduction

Understanding the movement of water through river and estuarial environments is critical for numerous environmental management problems. Examples include predicting the outcome and impact of silt disturbed by dredging operations; maintaining the health of fish populations by understanding the factors that affect their migratory patterns; and assessing the vulnerability of freshwater resources to contaminant release or other unpredicted events. This article describes a new approach to the design of low-cost floating sensors for hydrodynamic studies, leveraging low-cost commercial mobile phone technology for positioning, communications, and computation. Similar commercial mobile phone sensor platforms have recently been developed to provide low-cost sensor data collection [1], [2], [3], [4], [5] and monitoring of urban environments [6], [7], [8], [9]. A distinguishing feature of our work is the scale of the sensor fleet and the lack of dependence on supporting devices for mobility, data communication, or additional sensors.

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Fig. 1. Android drifters (6 of 70) awaiting deployment into a river

A. Drifting Lagrangian sensors

In situ sensing refers to sensing techniques where a device is in direct contact with the environmental phenomena it measures. In contrast, *remote* sensing refers to techniques like satellite imagery, in which measurements are taken from afar. *In situ* sensing in fluid environments is classified into *Eulerian* and *Lagrangian* techniques, using the terminology for the different reference frames in hydrodynamics. Eulerian sensors are fixed to the external reference frame, e.g., the river bank, and take measurements from the water as it moves by. Lagrangian sensors float freely in the fluid itself, and gather measurements about the water as it moves through the environment. Some Lagrangian sensors measure physical characteristics of the water in which they are immersed (e.g.

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TABLE I
FOUR GENERATIONS OF FLOATING SENSOR NETWORK DEVICES

Name	Generation 1 [18], 2 [15]	Generation 3 [19]	Android
Image			
Dimensions	11.5 cm diameter, 39.0 cm tall	13.0 cm diameter, 47.0 cm tall, 24.0 cm span across motor pods	13.0 cm diameter, 29.0 cm tall
Cost (parts)	\$ 1, 200	\$ 2, 500	\$ 305
Assembly time	60 h	10 h	2 h
Mission time	24 h	24 h	48 h
Computation	Gumstix Verdex: 400 MHz, 64 MB RAM, Linux 2.6	Gumstix Overo: 720 MHz, 512 MB RAM, Linux 2.6	Motorola DEFY: 800 MHz, 512 MB, Android 2.3
Communications	GSM, 802.15.4	GSM, 802.15.4	GSM
Propulsion	None	Twin parallel propellers	None

dissolved constituents or temperature), while for others, the primary data gathered is its position over time. A well designed Lagrangian sensor should act like an "ideal particle" in the water flow, thus the time series of its position allows direct estimation of the velocity of the water which it traveled through. In the hydrodynamics literature, such sensor devices are called *drifters*. Drifter design has always been constrained by the positioning and communications technologies available. Modern oceanography began using drifters based on underwater acoustic communication in the 1950s [10]. Acoustic technology dominated until 1978, when the Argus satellite service gave oceanographic researchers a global location and data uplink system [11]. Power, cost, and size constraints meant that Argos-based drifters [12], [13], [14] were better suited to oceanography than inland environments like rivers and estuaries. Global Positioning System (GPS) positioning and local radio frequency (RF) communication links are suitable technologies for inland studies. GPS-carrying river drifters have been the focus of development by the Floating Sensor Network (FSN) project at University of California (UC), Berkeley [15] and other groups [16], [17]. Studies in regions with well-developed civilian infrastructure, like the continental United States, can take advantage of the mobile phone network for communications. Table I shows the evolution of drifter designs at UC Berkeley. The drifter design in this article is to our knowledge the first design to use commercial mobile phones not only as the communication system, but as the positioning and computation system as well.

II. PHYSICAL FORM OF THE ANDROID DRIFTER

Recognizing that the basic requirements of a real-time Lagrangian drifter, that it can sense its own position and report it to a central location, are satisfied by consumer Android mobile phones, we designed an enclosure to hold such a phone. The form factor of the sensor was driven by three primary considerations: (1) that it be suitable as a Lagrangian flow sensor, (2) that the mass and volume distribution lead to a hydrostatically stable configuration to keep the phone oriented vertically and (3) that the phone be sufficiently high above the water line to ensure adequate reception. With respect to item (1), previous studies have indicated that a good Lagrangian sensor must provide a large, symmetric drag profile while in the water. Therefore we designed the external profile of the sensor to be a vertically oriented cylinder, with a mass/volume ratio that leaves 90% of the sensor submerged. With respect to items (2) and (3), initial experiments with a small vertically oriented cylinder did not keep the phone high enough above the water line to guarantee reception and indicated that a large distance between the center of mass and the center of buoyancy is necessary to maintain vertical orientation of the phone when the sensor is perturbed. Therefore, we chose a design with a center of mass (COM) located 9.40 cm from the base and a center of buoyancy (COB) 12.6 cm from the base. Aluminum ballast at the bottom ensures a large separation between the centers of mass and buoyancy as shown in Figure 2. The choice of material was driven primarily by durability and waterproofness. An assembly and bill of materials is

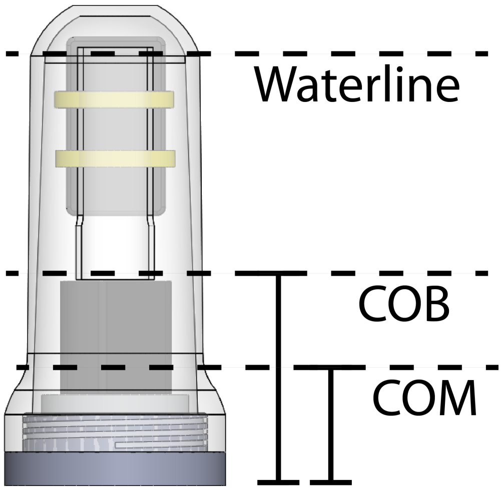

Fig. 2. Sensor dimensions and COM and COB locations

TABLE II
ANDROID DRIFTER BILL OF MATERIALS

#	Item	Price	Quantity
1	Duct tape handle	\$1	1
2	Upper PVC hull	\$25	1
3	Motorola DEFY	\$175	1
4	Rubber bands	\$1	2
5	PVC phone holster	\$15	1
6	Foam disk	\$1	1
7	LiPo battery	\$25	1
8	If-found placard	\$1	1
9	Aluminum disk	\$10	1
10	Delrin base	\$50	1
	Total	\$305	11

displayed in Table II and Figure 3. We chose pre-fabricated, ultraviolet (UV) stabilized polyvinyl chloride (PVC) upper hull and a machined Delrin lower hull with a red silicone O-ring (to ease inspection of the water-tight seal). The upper PVC hull is an off-the shelf component used in water filtration systems manufactured by Pentek. Leveraging such off-the-shelf components reduces cost and improves the reliability of the system. Delrin was chosen because it is easy to machine with computer numeric controlled (CNC) machines and only absorbs 0.2% of its volume in water during a 24 hour submersion, resulting in minimal changes to its dimensional tolerances. To ease assembly, notches were machined into the based of the lower hull that enabled two wrenches to be used during assembly/disassembly of the sensor. The Android phone is held near the top of the sensor with a machined PVC mounting tube. The typical residence time of water in the Sacramento-San Joaquin River Delta is 48 hours. The battery of the Android drifter was designed to allow for continuous usage of the GPS, accelerometer, and Global System for Mobile (GSM) module for 48 hours. This also provides sufficient time for a lost drifter to be located and retrieved. The following battery specifications were determined to meet this application. A Li-Ion, $115\,\mathrm{W\,h}$ at a $1\,\mathrm{A}$ rate, battery was chosen for its high energy density. The battery has a charging terminal of $7.2\,\mathrm{V}$, which also acts as discharging terminal if higher voltage is needed. The battery's main discharging terminal provides a regulated $5\,\mathrm{V}$ to a male right angle micro Universal Serial Bus (USB) that plugs into the mobile phone.

Fig. 3. Android drifter assembly with part numbers

III. Software

A. Overview

The software for the Android Drifter was written in Java, following the model of the Android platform's *Application Programming Interface* (API). The Android platform distinguishes two types of programs: *activities* and *services*. Activities are intended to be user-interactive, thus having a high execution priority, but can be terminated by the operating system if they lose focus in order to regain their resources. Examples of activities are web browsers or games. Services, on the other hand, are typically given less priority, but are the last to be terminated when the operating system is low on memory. Services run in the background and interaction with them must be through an activity. Examples of services are music players, battery monitors, or email notification applications. For our application we implemented the following three programs:

- *AndroidDrifterService*: Encompasses the main functionality of the Android Drifter, periodically transmitting and logging the last GPS position along with the valid flag indicating if the unit is upright.

- *AndroidDrifterActivity*: Provides the user buttons to s and stop the service and status indicators to determin data is being delivered properly.
- *ConfigureActivity*: Allows the user to configure the rameters (server address, port, update rate, etc.) of service.

A simplified Unified Modeling Language (UML) diagram provided in Figure 4. In the rest of this section, we descr the functionalities of the AndroidDrifterService in more det

B. GPS location collection

To collect the GPS location of the device, we used LocationManager API class and related libraries. We call API by requesting location change updates to a custom c back method and ask for minimum interval to receive upda Thus, our callback method is called about every second w a new location object. The latitude and longitude coordina are converted to UTM coordinates and store temporarily i the $last\_loc$ variable.

C. Valid flag calculation

The Android Drifter monitors its orientation to determ if its GPS position is valid, or drifting free in the wa or invalid, such as when it is being stored or transport The Android phone inside the Android Drifter has a fixed orientation, therefore, the phone's orientation moves along with the orientation of the drifter as a whole. Given that the units are typically stored on their sides in containers and are upright when floating, we can use the phone's built in accelerometer to determine when the drifter is in either of these two states. The x-axis of the accelerometer points to the right side of the phone's screen, the y-axis points to the top of the phone, and the z-axis points out of the screen of the phone. To collect the accelerometer readings from the phone we used the SensorManager API class and related libraries. Similar to the LocationManager class, we configured a callback to be provided updates at the fastest possible rate. On the incoming readings (raw_x, raw_y, raw_z) we implement a variant of the exponential moving average:

$$\begin{aligned} a_x &\leftarrow (1 - \alpha dt) \cdot raw_x + \alpha dt \cdot a_x \\ a_y &\leftarrow (1 - \alpha dt) \cdot raw_y + \alpha dt \cdot a_y \\ a_z &\leftarrow (1 - \alpha dt) \cdot raw_z + \alpha dt \cdot a_z \end{aligned}$$

where dt is the time since the last sample and α is the degree of weighting decrease. Unlike the standard exponential moving average, samples are also scaled by the sampling interval because the Android operating system does not provide samples at a consistent rate. The weighting factor $\alpha = 0.001$ was chosen as a tradeoff between responsiveness in detecting placement in water and storage and effectiveness in filtering out bumps and shakes. We then compute the valid flag representing these two states as:

$$valid \leftarrow \begin{cases} 1 & \text{if} \quad a_y > |a_x| \text{ and } a_y > |a_z| \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

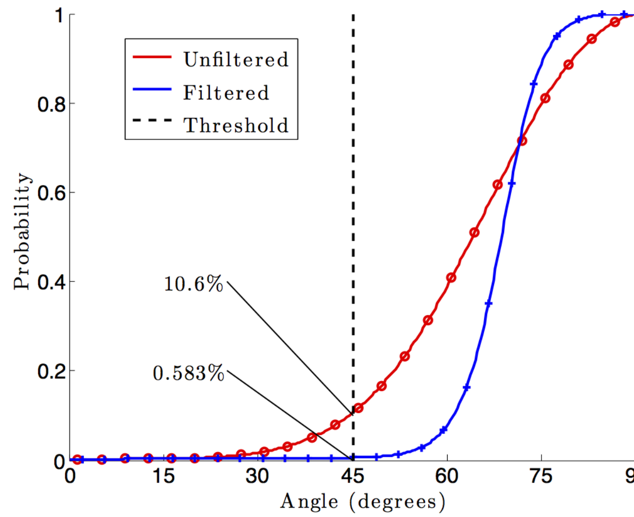

Fig. 5. CDF of the angle calculated from the unfiltered (red circles) and filtered (blue plus signs) accelerometer signal recorded by the Android phone. Unit was floating upright for the entirety of the 14 hour test. Black line shows the threshold value on which the software decides if the GPS position is valid.

Therefore, if the phone's longest dimension is aligned with the gravity vector and upright, $valid$ becomes 1, whereas if the phone is on one of its other sides, $valid$ is 0. Without the filter, we find that there are many false-negatives, i.e. the drifter reports $valid = 0$ when it should report $valid = 1$. The errors are caused by noisy accelerometer signals which can be attributed to wave action buffeting the drifter as well as normal noise from the sensor. We ran a study to determine the effect of the filter described above on the false-negative rate. For this test, the drifter was moored floating upright for 14 hours while logging accelerometer samples. Sampling intervals during this study had a mean of 203 milliseconds and a standard deviation of 17 milliseconds. We then calculate the raw and filtered pitch angles ϕ_{raw} and ϕ using the following formulae:

$$\begin{aligned} \phi_{raw} &= \tan^{-1}\left(\frac{raw_y}{\sqrt{raw_x^2 + raw_z^2}}\right) \\ \phi &= \tan^{-1}\left(\frac{a_y}{\sqrt{a_x^2 + a_z^2}}\right). \end{aligned}$$

We evaluate the arctangent function $\tan^{-1}\left(\frac{y}{x}\right)$ using the two-argument function $\text{atan2}(y, x)$ common to many computer languages in order to place the angle in the correct quadrant. The cumulative distribution functions (CDF) of these two signals are plotted in Figure 5, along with the $45°$ threshold implied by Equation (1). From this, we calculate that the probability of false-negatives for the unfiltered data and filtered data is 10.6% and 0.583%, respectively. Thus, we conclude that the filtering is necessary to practically use the accelerometer as a tilt detector for determining whether the drifter is floating in the water or stored in its box.

D. Data transmission and Logging

The Timer API class is used to schedule a callback function periodically at a user-defined interval (typically 5 seconds). In

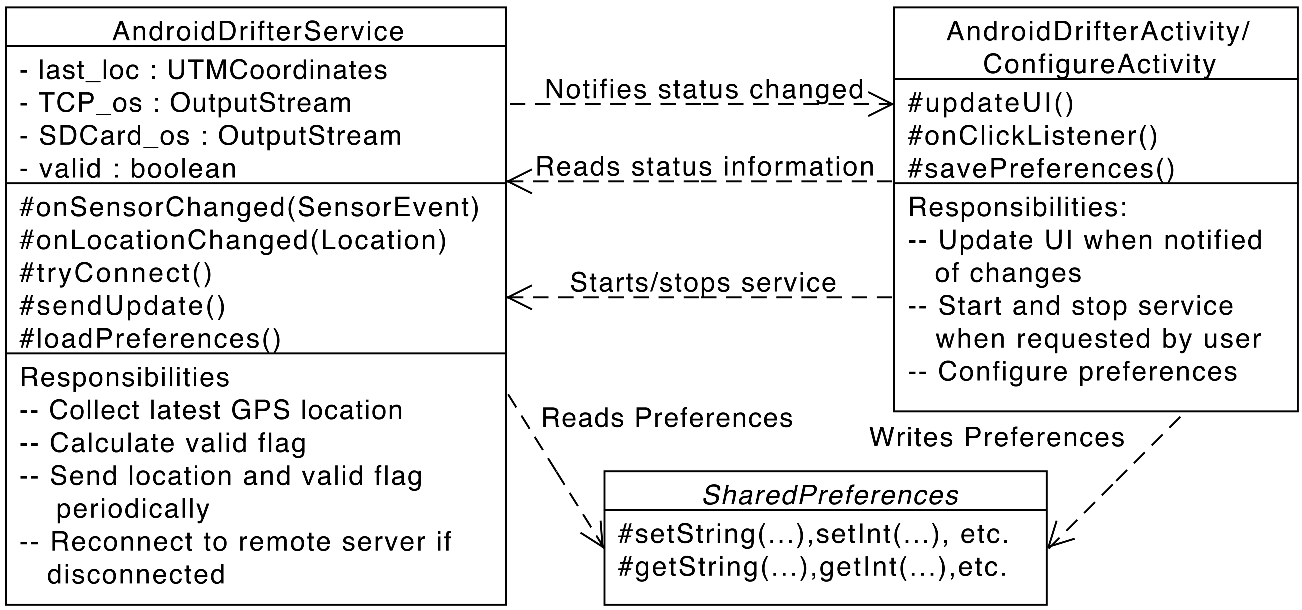

Fig. 4. Simplified UML diagram showing interactions between software components of the Android drifter

this callback, sendUpdate(), a *type-length-value (TLV)* string is constructed, delimited by the forward slash character. An example of such a string is:

```
id/A78/ts/1334251708/x/630062.63/
        y/4233832.13/zn/10/valid/0/<LF>
```

where <LF> is the line feed character 0x0A. Here, the unit with ID A78 is reporting that on April 12, 2012 at 17:28:28 Greenwich Mean Time (1334251708 seconds since January 1, 1970), it was at UTM Coordinates 10N 630062.63 4233832.13, and that the data is invalid. Since this is about 10:30 a.m. Pacific Standard Time, this corresponds to a time when the unit was still in storage in a container, waiting to be deployed. The phone attempts to both write this string to a file on the phone's external memory card and send the string to a remote server over a transmission control protocol (TCP) connection. If either method is disrupted, the phone attempts to reestablish the file-handle or socket connection, respectively. When the phone does not have a GPS lock, it will still write data to the file and TCP connection at the defined interval, reusing the last GPS sample sent (or populate the fields with 0 if a lock was never achieved since the service was started). This assists later analysis as we can determine when GPS functionality was compromised and distinguish problems with the GPS from other parts of the program.

IV. Applications

The Android drifters have been on over four missions in the Sacramento-San Joaquin River Delta. The FSN and Stanford University's Environmental Fluid Mechanics and Hydrology Department have each managed two missions independently. The experiments conducted by Stanford University were focused on water flow through channel junctions in the Sacramento-San Joaquin River Delta. In over 1300 hours of operation, no drifter has leaked and only two Android drifters have been lost. Operation hours are totaled for the entire fleet of 70 Android drifters. One drifter was lost on August 9th, 2011 and found by a local Sacramento-San Joaquin River Delta resident June 24th, 2012 in the water with no signs of leakage after 316 days. This is a strong demonstration of the Android drifters mechanical hardware durability. On May 9th, 2012, 70 Android drifters were deployed for $8\,\mathrm{h}$ 8 hours over a span of over $5.5\,\mathrm{km}$ along the Sacramento River and Georgiana Slough located near Walnut Grove, California. Android drifters were deployed from the public dock before the Sacramento River-Georgian Slough junction and retrieved down river of each channel by boats each with a crew of three (one boat captain and two Android drifter retrievers) and pole nets. Before the junction, Android drifters were quickly retrieved and deployed so as to send roughly half of the fleet down each channel. Once retrieved, Android drifters were then returned to the dock and the boats returned to their retrieval locations (Figure 6).

V. Future work

The next generation of the Android Drifter will incorporate a serial connection between the mobile phone and a microcontroller, allowing the drifter to actively control its propulsion. The microcontroller will provide the real-time processing necessary for a differential drive configuration implementing heading control (currently used on the Generation 3 Drifter [19]), while the mobile phone will provide reliable communications, high processing power, and a user interface

(a) Deployment

(b) Passive sensing

(c) Retrieval

(d) Redeployment

Fig. 6. Android drifter usage

in an inexpensive package. The computation and positioning capabilities of the mobile phone provide a means to better estimate the position of a floating sensor through the application of a Kalman Filter algorithm. With the addition of a wired serial port, robotic control becomes possible. We have experimented with prototypes in which a SparkFun Electronics board links the Android phone to a microcontroller equipped with an XBee Radio in order to provide additional communication between Android drifters and Generations 3 drifters with the IEEE 802.15.4 wireless standard in the 2.4 GHz frequency band.

VI. Conclusion

The Generation 3 drifters were designed with custom electronics and were not tailored for external academic research applications, decreasing their reliability, increasing their cost, and reducing their manufacturability. By replacing the custom electronics of Generation 3 drifters with a mobile phone, the Android drifters were able to decrease cost, increase reliability, and increase manufacturabilty. Manufacturability and cost was improved by limiting the need for source electronic components and decreasing the assembly time and complexity (Table I). Reliability was increased by a simple and robust design with few points of failure. Android drifters have proven to be an inexpensive solution to water flow sensing as seen by the BOM in Section II. They provide a solid infrastructure for mobile phone based robotics and sensor networks due to their high reliability made evident through their mission time mentioned in Section IV. Mobile phones offer many capabilities that can be integrated into a variety of projects. They are relevant to any research group that has an application requiring computation, communication, and positioning. In this application of mobile phones, computation is limited. Reliable GSM communication to remote servers was essential in providing real time sensor measurements as well as ensuring hardware placed in harsh environmental conditions was easy to maintain contact with. The accelerometer sensor in the Android phones allow us to determine when the phone's samples are valid (floating in the water) or invalid (in storage). The GPS unit provided the positioning that was critical in estimating the flow of water. Future work with the Android drifters will focus on using a serial link between the mobile phone and microcontroller in order to drive a propulsion system similar to the ones used on previous generations of drifters.

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