AFFORDABLE WATER QUALITY ANALYSIS: A PROPOSED FRAMEWORK FOR THE DEVELOPMENT AND REGULATION OF LOW-COST WATER QUALITY MONITORING DEVICES

by

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Abstract

Access to adequate supplies of potable water is a key driver of human health. Physical and chemical treatment processes are frequently necessary to make water safe to drink. Monitoring of water before, during, and after treatment is an essential component of the provision of potable water, and most aspects of water quality monitoring require electronic devices to augment human senses. Every nation sets rules governing the treatment and monitoring of drinking water, in an attempt to continuously ensure potability of drinking water supplies. Presently, however, the regulations governing the design of common electronic devices for water quality monitoring are developed and published by just two organizations – the US Environmental Protection Agency (EPA) and the International Organization for Standardization (ISO). The implications of this regulatory situation on drinking water quality monitoring, particularly in low-resource settings, are largely (perhaps completely) unaddressed in existing literature.

Turbidity, which may be summarized as cloudiness in a body of liquid due to the scattering of light by particles suspended in that body, is internationally recognized as a simple and useful monitoring parameter for drinking water treatment. Using turbidity as an exemplar, this dissertation examines the structure of regulations governing the design of water quality monitoring devices, and the potential impact that regulatory structure has on the design, fabrication, and marketing of water quality monitoring devices, including both closed-source and open-source technology. National turbidity monitoring requirements for several nations, and the turbidity guidelines promulgated by the World Health Organization, are compared. The EPA and ISO turbidimeter regulations are also examined in relation to these national and international turbidity monitoring requirements. Design variables and requirements are identified which are generally necessary to ensure a properly functioning turbidimeter, but which are not explicitly stated in EPA and ISO turbidimeter regulations.

Aspects of the commercial turbidimeter market, and EPA and ISO turbidimeter regulations, which are likely burdensome for water quality monitoring efforts in low-resource settings (such as rural communities in developing countries), are explored – perhaps chief among these being cost. While production of open-source turbidimeter designs provides a potential solution for turbidity monitoring in low-resource settings, open-source turbidimeter design efforts are currently far from able to meet global needs.

To provide supplementary regulatory requirements for EPA and ISO turbidimeter standards, and to spur the development of market-ready open-source turbidimeter designs, a framework titled the Affordable Water Quality Analysis (AWQUA) device development is proposed. It consists of a turbidity-specific regulatory section, and a general water quality monitoring device development guidance section. Proper use of this guidance section is intended to strengthen open-source water quality monitoring device development efforts and encourage the production of device documentation suitable to demonstrate compliance with the regulatory section.

An important contribution of this dissertation effort is the development and detailed description of four different examples of novel, low-cost, open-source water quality monitoring devices that motivated the proposed supplementary framework, informed its design, and serve to illustrate its application. First, a low-cost, open-source handheld turbidimeter based on a simple digital light detection sensor is detailed and discussed. The design, fabrication, and testing of this device served as a motivator for the development of the proposed supplementary turbidimeter development guidelines proposed. The turbidimeter nearly meets international regulatory guidelines, was fully described in a peer-reviewed publication, and is believed to be the most detailed open-source design of a digital turbidimeter publicly available (at the time of this writing) and yet contains several subtle but critical design flaws that are unaddressed in current national and international turbidimeter regulations. This prototype thus motivated and informed the design of the proposed new regulatory framework. Subsequently, three other promising open-source water quality monitoring designs were developed, fabricated, and evaluated under the AWQUA Framework: (1)

a second low-cost open-source handheld turbidimeter, based on a highly precise light-to-voltage analog sensing setup; (2) a highly compact low-cost open-source inline turbidimeter, designed for continuous immersive monitoring of turbidity in surface waters; and (3) a low-cost open-source jar tester – a device used to evaluate certain physical and chemical treatments employed in drinking water treatment to reduce turbidity. These designs and the associated framework that grew from them are contributions toward the provision of “Affordable Water Quality Analysis” (AWQUA) capabilities for communities in low-resource settings.

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AC: Alternating Current

ADC: Analog-to-Digital Converter

ASTM: American Society for Testing and Materials

ATP: Alternative Test Procedure

AWQUA: Affordable Water Quality Analysis

BGA: Ball-Grid Array

BLEND: A 3D image file format

BOF: Bill of Fabrication

BOM: Bill of Materials

BRD: Board, an EagleCAD circuit board file format

C: Celsius

CAD: Computer-Aided Drafting

CAM: Computer-Aided Manufacturing

CAMO: Construction, Affordability, Maintenance, and Operation

CAS: Cost at Scale

CNC: Computer Numeric Control

DC: Direct Current

DXF: Drawing Exchange Format, a CAD file format

EC: European Commission

EEPROM: Electrically Erasable Programmable Read-Only Memory

EPA: United States Environmental Protection Agency

EU: European Union

F3D: Fusion 3D Design, a CAD file format

FNU: Formazin Nephelometric Unit

GIS: Geographical Information Systems

GPS: Global Positioning System

GSM: Groupe Spécial Mobile

Hz: Hertz

I2C: Inter-Interconnected Bus

IGERT: Integrative Graduate Education and Research Traineeship

ISO: International Organization for Standardization

JTU: Jackson Turbidity Unit

LCD: Liquid Crystal Display

LED: Light-Emitting Diode

LMIC: Low- and Middle-Income Countries

LOD: Limit of Detection

LRS: Low-Resource Settings

mAh: milli-Ampere hour

NGO: Non-Governmental Organization

nm: Nanometer

NSF: National Science Foundation

NTU: Nephelometric Turbidity Unit

OBJ: Object, a geometry definition file format

OGC: Open Geospatial Consortium

OLED: Organic Light-Emitting Diode

OSHWA: Open-Source Hardware Association

PCB: Printed Circuit Board

PPM: Parts Per Million

PWM: Pulse-Width Modulation

QA/QC: Quality Assurance and Quality Control

RPM: Revolutions Per Minute

SAT: Standard ACIS Text, a geometric model file format

SCAD: Solid CAD, a file format for procedurally defined 3D objects

SD: Secure Digital

SMS: Simple Message Service

SPI: Serial Peripheral Interface

STL: Stereolithography file format

UN: United Nations

USB: Universal Serial Bus

USED MILQ: User, Sampling, Environment, Device, Measurement, Interaction, Legal, Quality assurance and quality control

UV: Ultraviolet

V: Volt

WASH: Water, (And) Sanitation, Health

WHO: World Health Organization

µm: micrometer

Chapter 1: Introduction

1.1 Water resources for human consumption

Humans need to consume water regularly to survive, and in basically all cases this water is obtained from the earth's environment. Water sources for humans are typically divided into groundwater sources beneath the earth's surface such as aquifers, and surface water sources such as rivers and lakes. Such fresh (non-saline), liquid water sources constitute less than one percent of total global water resources (Clausen 2017). Salt water that has been desalinated is a promising source of drinking water for humans, although its use is limited by the cost, energy requirements, and waste production of current desalination technologies (Ghaffour et al. 2013). Human consumption is but one of several daily personal needs for water (others include bathing and cooking) and daily personal needs are only some of the drivers of global water consumption, which also include agriculture and industry. Hereafter, liquid water obtained from earth's environment that has not been treated or purified in some manner will be referred to as "natural" water, and focus will be given chiefly to water as a daily personal need (particularly for consumption).

1.2 Treatment and monitoring of drinking water for human health and safety

Although commonly perceived by many as a simple homogenous substance, natural water on earth may have an incredibly complex and heterogenous composition, containing diverse loads of dissolved minerals and salts, suspended minerals, micro-organisms, and non-living organic matter (Stumm & Morgan, 1970). Moreover, the heterogenous constituents in natural water on earth may vary dramatically from one location to the next, or in a single location over time (Benjamin & Lawler 2013).

The concentrations of these constituents in natural water may prove injurious if a sample of such water is consumed by humans – a very important and interesting field of study that is unfortunately only touched upon in this dissertation. For our purposes, it will suffice to say that natural water on earth typically needs physical and chemical treatment to ensure that regular consumption by humans does not result in significantly elevated risk of injury. Natural water that has been subjected to such physical and chemical treatments (discussed below) will hereafter be referred to as "treated water" (and natural water will thus be defined as "untreated water").

Drinking water treatment typically consists of physical and chemical processes to remove unsafe and undesired constituents from water before consumption. As an abstracted process, drinking water treatment often contains a series of sequential processing steps, which for a surface water sources may include:

1. *Screening* – the removal of larger suspended objects in the water (several millimeters or more in diameter);
2. *Coagulation and Flocculation* – the addition of chemical agents (coagulants) that facilitate adhesion among particles, allowing the subsequent aggregation of a larger number of smaller suspended particles in the water into a smaller number of larger suspended particles, aided through gentle mechanical agitation (flocculation) of the water;
3. *Sedimentation* – the process of allowing and assisting the settling of larger suspended particles (including newly coagulated/flocculated particles) to the bottom of the water body, where they may be physically removed;
4. *Filtration* – the removal of smaller suspended particles not removed by sedimentation, through their adhesion to the media (e.g. sand grains) within granular media filters (such as a large column of sand) or through the sieving action of membrane filter sheets;
5. *Chemical adjustment* – the addition of chemical agents for various purposes (e.g., to reach a desired pH) prior to distribution or additional treatment;

6. *Disinfection* – typically one of the last steps in treatment, disinfection involves the addition of a chemical or physical agent (e.g., chlorine dioxide or UV radiation, respectively) to inactivate pathogens that may remain in the water, or which may be introduced during distribution and storage.

For groundwater sources that are well isolated from the influence of surface water there may be less need for particulate removal (and potentially more need for removal of dissolved constituents), but monitoring of the water treatment processes and the quality of the treated water is just as critical. The above list is by no means exhaustive but represents a large portion of the treatment activities carried out globally by centralized water treatment plants before distribution via pipes, trucks, or small containers. Drinking water treatment may also be carried out at a household or individual level, also consisting ideally of a sequential set of treatment processes.

Whether at household-scale, or city-scale, drinking water treatment places a significant technical and operational demand on treatment technicians. It is essential to inspect a given water source prior to treatment, to determine what sorts, and what quantities, of physical and chemical treatment processes are needed to make water safe for human consumption. Given the physical and chemical complexity of natural water sources, it is further essential that process monitoring is regularly conducted, from the untreated source water, through the chosen treatment steps, and during distribution and storage of the treated water. Such monitoring requires "goal states" for the treated drinking water, which are typically specified by regional and national governments for the protection of human health.

1.3 Standards for treatment and monitoring of drinking water

Likely every nation has national drinking water treatment and monitoring standards in their respective national laws. Representative examples of national drinking water treatment standards include the regulatory frameworks of the United States Environmental Protection Agency (EPA;

see NPDWR 2008) and the European Commission (EC; see Ljujic & Sundac 1998). The World Health Organization (WHO) also publishes extensive guidelines for water quality treatment and monitoring, though these guidelines do not have regulatory scope (WHO 2014). These frameworks have in some instances informed respective guidelines of other nations (Jarraud et al 2015), though nations generally set their own regulatory frameworks for water quality monitoring.

The EPA's National Primary Drinking Water Regulations regulate the presence of 94 contaminants in water distributed by regulated drinking water provider in America, including microorganisms, turbidity, disinfectants and disinfection by-products, organic and inorganic chemicals, and radionuclides (NPDWR 2008). Fifteen secondary standards are also laid out by the EPA, which cover contaminants which may cause negative aesthetic and cosmetic effects in drinking water, or which may pose technical issues impairing the effectiveness of treatment techniques. The EPA also promulgates treatment-specific and source-specific regulations. The Long-Term 2 Enhanced Surface Water Treatment Rule (LT2), for example, aims in part to control the pathogen Cryptosporidium through the use of specific treatment techniques and microbiological and turbidity monitoring (NPDWR 2008).

Regulatory standards for several other nations will be comparatively examined in Chapter 2.

1.4 Devices for drinking water monitoring

Human senses alone are not particularly well suited for water quality monitoring. We humans can feel relative changes in water temperature with our hands, or smell the presence of chlorine in water, but we generally cannot determine water temperature or chlorine dosage with an accuracy even close to that of a dedicated electronic meter. We may judge the dirtiness of water by how cloudy it is, but our eyes respond to light logarithmically instead of linearly, and visual acuity varies from one observer to the next. We cannot even gauge flow rate accurately without at least a container and a stopwatch.

Regulatory frameworks governing the treatment and monitoring of drinking water function (ideally) as a toolset for protecting public health, and monitoring of drinking water depends on physical and chemical augmentation of human senses. The shapes that such devices take are influenced by ergonomic factors, regulatory sampling requirements (such as frequency and accuracy), the current state of technology, and market considerations. Thus, for many water quality parameters there may be more than one type of monitoring device on the market. For example, pH monitoring may be accomplished with a chemically laden paper test strip, a bottle of indicator dye, a handheld digital meter, or an inline probe. These devices may vary dramatically in their upfront cost and cumulative per-test cost over the life of a monitoring program -- a set of paper test strips costs significantly less than an inline probe, but for a decade-long monitoring program the cumulative supply and labor costs of conducting daily tests with paper strips may make the inline probe a more affordable option overall.

1.5 Global figures on consumption of unsafe drinking water

The UN General Assembly has recognized “the right to safe and clean drinking water and sanitation as a human right” (UNGA 2010), but it is a right that must be won daily in all inhabited corners of the world. Effective water treatment cannot reliably or sustainably be accomplished without monitoring devices to augment human senses, and the forms and prices of these devices are shaped by regulatory requirements and market forces. The availability of safe drinking water is fundamental to human health, and supports key activities such as handwashing, bathing, and food washing. Where water quality monitoring devices cannot be made affordable or maintainable, effective monitoring cannot be guaranteed and human health and wellbeing is at risk (Prüss-Ustün et al. 2014). Currently, an estimated 700 million people lack access to “improved” sources of drinking water under UN definitions (which are a common infrastructure development benchmark, but do not guarantee the potability of water), while an estimated 2 billion people regularly consume drinking water that fails international standards for potability (Bain et al. 2014).

Chapter 2 centers on a discussion of potential mismatches between regulatory requirements, market forces, and human needs for turbidimeters – one type of water quality monitor. Lack of monitoring is but one impediment to ensuring that people have adequate supplies of potable water, and this dissertation aims to address only a small aspect of global water quality monitoring needs. Still, it is hoped that the discussion ahead may be of use to the reader, and perhaps help to bring attention and clarity to a problem of global scope.

1.6 Motivation and Objectives

1.6.1 Motivation

This topic of this dissertation is probably the sixth that I've mooted during my doctoral studies. When I began my graduate studies and research at Johns Hopkins University, I was fascinated with GIS and envisioned a documentation system and decision engine that could be used to visualize and help people learn from "WASH failures" – the myriad dead or unsustainable Water, Sanitation, and Hygiene (WASH) infrastructure improvement projects that had been constructed by governments, NGOs, and charities in recent years. (See Sutton 2004 for a sample, or visit Improve International's "Sad Stats" webpage [Improve International 2012] for a wider listing.) When the scale of effort required to pull the myriad facts on those WASH failures out of technical reports and expert interviews and into a GIS framework became apparent, I suggested focusing instead on data transmission and planning tools for water infrastructure improvement, to help ensure that *new* development projects would be done well.

During a visit to some small-scale water treatment plants in Honduras I noted that record-keeping was being done on paper, so I constructed such a data transmission tool to help water treatment technicians in rural areas text water treatment performance indicators directly to a computer for remote visualization and analysis by engineers. This was a reasonable success (which ran for four years until someone else finally built a better tool), but I was soon struck by the uneasy realization that the data flowing through that transmission tool were acquired with commercial water quality monitoring instruments paid for by American organizations with research and charitable interests in the water treatment plants I had visited. Without those commercial monitoring devices, the data flowing through my transmission tool would be garbage (or maybe just absent entirely). Cheap and effective data transmission is an important problem in the developing world, but Facebook and Google work every day to solve it. There were no titans of industry, it seemed, working to build cheaper water quality monitoring devices.

“Why is this so?” was probably the best question to ask at that point, but instead I asked “How can I fix this?” A couple of reasonable early prototypes led me down a twisting path of electrical engineering, firmware programming, and 3D printing. Monitors for turbidity (the cloudiness of water), or “turbidimeters,” were an early and enduring focus of this line of work, as turbidity is one of the most important indicators of relative success in surface water treatment. As the WHO (2017) recently noted: “Turbidity is an extremely useful indicator that can yield valuable information quickly, relatively cheaply and on an ongoing basis. Measurement of turbidity is applicable in a variety of settings, from low-resource small systems all the way through to large and sophisticated water treatment plants.” Turbidimeters also have a negligible per-test cost but a very high up-front cost, making them good targets for cost-reduction efforts.

With the help of undergraduate assistants, I worked over the course of the next four months to develop a prototype turbidimeter that performed well in the lab; nearly well enough, it seemed, to meet international regulations. The design was published in a peer-reviewed open-access journal, and my team continued to make improvements. As we moved forward in our work, testing new models in the lab and in various field sites, we began to realize the fragility of our published device. It *could* be made to usefully function as a handheld turbidimeter, with a lot of calibration and care, but it was certainly not a robust monitoring solution.

“How can I fix this?” I asked, but this time I also wondered “Why is this so?” If I can create a novel turbidimeter that is deemed publishable, which nearly meets regulatory requirements and has generated significant interest and some media buzz, but which is in practice an unreliable device in ways that would not be obvious to the average consumer – what could an inobservant, or unscrupulous, engineer do in this situation? To address broader issues surrounding this device development work (and to ensure I could graduate in a reasonable amount of time), I shifted my dissertation focus once again to: (1) examining the shape of existing regulatory frameworks and discussing how these might be amended to drive fulfillment of the sore global need for affordable, tailorable, easily repairable turbidimeters and other water quality monitoring devices; and (2) continuing to work in device construction to attempt to meet some piece of that sore global need.

1.6.2 Objectives and Questions

1. Examine turbidity as a key parameter of global water quality monitoring:

    (1.1) What are the current national and international guidelines for monitoring turbidity?

    (1.2) How well do current regulatory standards for turbidimeters reflect the global need for these devices?

    (1.3) What are current financial and logistical challenges for monitoring turbidity in low-resource settings?

    (1.4) How well is open-source development of turbidimeters addressing the global need for turbidimeters?

2. Propose guidelines and standards to guide the development of low-cost and open-source water quality monitoring devices – the Affordable Water Quality Analysis (AWQUA) framework:

    (2.1) What would be the rationale and conceptual components of such a framework?

(2.2) What minimum performance targets should be expected of low-cost and open-source turbidimeters?

(2.3) What helpful or necessary regulatory language for the development of low-cost and open-source turbidimeters is not explicitly stated in existing national and international turbidimeter design standards?

(2.4) What is needed of a documentation framework, for the development of low-cost and open-source turbidimeters, that can be used to certify compliance with the AWQUA Framework?

3. Present examples of open-source water quality devices at different stages of development, within the context of the AWQUA Framework These are not questions so much as the beginnings of answers:

(3.1) A low-cost, open-source handheld turbidimeter that is more robust than my lab's first published turbidimeter

(3.2) A low-cost, open-source inline turbidimeter that can be reliably used for immersive turbidity monitoring in surface water bodies.

(3.3) A low-cost, open-source jar tester (used to gauge coagulant dosage).

1.7 Organization of this dissertation

Chapter 1 of this document is an attempt to provide the reader with a broad-scale overview of the importance of physical and chemical treatment processes that are typically employed around the world to produce potable water, and emphasis is given to the importance of monitoring these treatment processes. In Chapter 2, examples of national and international policies that guide the treatment of drinking water and the monitoring of drinking water quality are examined; the shortcomings of current drinking water quality monitoring in many lower-income areas around the world are discussed, and potential policy and technology underpinnings of these shortcomings is explored. Chapter 3 proposes a technical policy framework, intended as a supplement to commonly referenced international drinking water treatment and monitoring guidelines, which could help guide the development of monitoring devices that could help bridge the drinking water quality monitoring gap between higher-income and lower-income areas of the world. Chapters 4 through 7 give examples of four novel, low-cost, open-source water quality monitoring devices that served to identify the need for the proposed technical policy framework and, importantly, inform its design and demonstrate its application. Finally, Chapter 8 presents a brief synthesis of the previous chapters and discusses future and implementation research directions.

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Chapter 2: An examination of turbidity as a key parameter of global water quality monitoring

2.1 Chapter foreword

This chapter focuses on regulatory, geographic, economic, and commercial factors that give rise to the current state of the international market for electronic (and predominately handheld) turbidimeters. There are many water quality monitoring needs that are largely unmet in lower-income settings around the world; too many, regrettably, for thorough discussion in one dissertation. Turbidity was chosen as a focal point for a few reasons – turbidity is a key water quality treatment monitoring parameter, basic handheld turbidimeters have high equipment costs but practically negligible operating costs, and non-electric methods for turbidity monitoring are generally unsatisfactory for protection of human health (WHO 2017, EPA 1999). Additionally, turbidity is the only water quality parameter identified by the WHO as a key operational monitoring parameter in each phase of conventional centralized water provision (including raw water, coagulation, sedimentation, filtration, disinfection, and distribution; see WHO 2017, Table 4.3). The author hopes that this examination and the analysis that accompanies it may in some respects usefully address broader issues and opportunities for global water quality monitoring, and guide or motivate others to improve access to affordable turbidimeters (and other monitoring devices) in low-resource settings (LRS).

Note: Section 2.2 is from the manuscript An Affordable Open-Source Turbidimeter (*Sensors* 14.4 (2014): 7142-7155), for which the author of this dissertation is lead author (Kelley et al. 2014).

2.2 Introduction to turbidity

Turbidity refers to the cloudiness of a fluid medium and is quantified by the intensity of light scattered by particles suspended in the medium (APHA & AWWA 1995). While pure water consists only of H_2O molecules, a very small fraction of which are in ionic states at any given point, natural water typically includes many other substances. These additional substances are logically separated into dissolved and suspended solids, the distinction typically being whether a molecule or particle of a given substance can pass through a reference pore size (typically 1.5 micrometers [EPA 1999b]). Water inherently has a slight blue color due to absorption and scattering of light, and dissolved particles in natural water such as tannins and humic acids also selectively scatter light and can give water much more intense apparent color.

For the purposes of water quality monitoring, the American Water Works Association defines turbidity as a "nonspecific measure of the amount of particulate material in water" including "clay, silt, finely divided organic, and inorganic matter" (Letterman 1999). The particles principally responsible for turbidity in water may have high specific surface area, and often represent the majority of chemical contamination in a water supply as they can adsorb water quality contaminants such as heavy metals or pesticides (O'Melia 1980). Perhaps more importantly, such particles provide microscopic refuges for pathogens, absorb and scatter ultraviolet light (rendering UV light less effective as a disinfectant), and often have a high fraction of natural organic matter, which can consume the oxidizing power of chemical disinfectants such as chlorine and ozone and can form toxic by-products in the process (Richardson et al. 2007). The particles that cause turbidity can thus significantly impair the effectiveness of disinfection processes for drinking water treatment. Additionally, reductions of turbidity are good indicators of treatment efficacy and increases in turbidity during treatment or distribution of drinking water are general indicators of increases in potential sources of human health risk. For all of these reasons, turbidity is widely recognized, both in the relevant engineering literature and in regulations promulgated by the United States Environmental Protection Agency (EPA), as a principal indicator of the cleanliness and potability of water (EPA 1999).

Turbidity is most commonly quantified by the Nephelometric Turbidity Unit (NTU), or the equivalent Formazin Nephelometric Unit (FNU). Nephelometry refers to the process of aiming a beam of light at a sample of liquid and measuring the intensity of light scattered at 90 degrees to the beam, while turbidimetry refers to the process of measuring the attenuation of light passing through a sample of liquid; devices based on nephelometry or turbidimetry are commonly referred to as turbidimeters (ISO 2016). Further, the NTU/FNU scale is defined in nephelometric analysis by comparison against reference colloidal suspensions of the polymer formazin (EPA 1993). The human eye can detect turbidity levels down to roughly 5 - 10 NTU. Small samples of water with turbidity lower than this will appear clear to the human eye, however such samples may still contain a concentration of colloidal particles sufficient to impair disinfection efforts and may carry a load of contaminants or pathogens sufficient to cause serious human illness (EPA 1999). Lechevallier et al. (1981) investigated the relationship between turbidity and the ability of chlorinated water to inactivate coliform bacteria and demonstrated that reducing turbidity from 8 NTU to 1.5 NTU increased chlorination efficacy by over two orders of magnitude. (Other parameters such as the time that pathogens spend in contact with disinfectants are crucial determinants of inactivation efficacy but are beyond the scope of this paper.) Current EPA regulations stipulate that conventionally treated surface water in the USA must be regularly sampled for turbidity, that only 5% of samples in a given month may show turbidity greater than 0.3 NTU, and that no sample may show turbidity in excess of 1.0 NTU (EPA 1999). Other countries employ different standards, and the World Health Organization (WHO) recommends that turbidity levels be less than 1.0 NTU prior to disinfection (ISO 2016). The gap between human visual detection limits and safe exposure limits has led to the development of electronic devices that employ nephelometry to measure turbidity. Standards for the design and calibration of these devices, which are commonly known as turbidimeters (or nephelometers), have been specified in EPA Method 180.1 (EPA 1993) and International Organization for Standardization regulation ISO 7027 (ISO 2016).

Turbidimeters typically contain: (1) a light source that is directed through a liquid sample; (2) a chamber to hold the liquid sample; and (3) one or more photodetectors placed around the chamber. Three archetypal turbidimeter design patterns are diagrammed in Figure 1. A single-beam turbidimeter only measures scattered light, while ratio and modulated four-beam turbidimeters also measure transmitted light (the latter alternating between two light sources). Single-beam turbidimeter designs have upper detection limits that are inherently lower than those of ratio or modulated four-beam turbidimeter designs, since the intensity of scattered light varies non-linearly with turbidity. That is, in very clear water an increase in turbidity will result in more light scattering, but for sufficiently turbid water the addition of more colloidal particles may increase multiple scattering such that a scattered-light photodetector may report an apparent decrease in turbidity. Ratio and modulated four-beam turbidimeters normalize readings of scattered light using readings of transmitted light; series of these normalized values can remain linear even at very high turbidities (EPA 1999).

Most turbidimeters use either a near-infrared LED or an incandescent lamp as a light source (some use both, interchangeably). Near-infrared light (typically in the range of 800-900 nm) is in some ways preferable to visible light for turbidity measurement, due to the inherent relationship between light wavelength, the size of particles in a fluid medium, and the light-scattering behavior of those particles. The scattering of light in a fluid medium by particles with diameters that are much smaller than the wavelength of the light source (Rayleigh scattering) varies inversely in intensity with the fourth power of the wavelength of the light source. It is due to this phenomenon, for example, that we perceive the color of the sky, which results from light scattering by atmospheric gases. The scattering of light in a fluid medium by particles with diameters that are at least a significant fraction (0.25 is an arbitrary but illustrative cutoff) of the wavelength of the light source (Mie scattering), however, does not vary significantly with the wavelength of the light source. The Mie scattering of light by cloud droplets, for example, gives clouds their shades of white and gray (Kerker 1969).

Clay particles in water range from roughly 60nm up to 2µm, and silt particles from 2µm up to 62.5µm (Wentworth 1922). Near infrared light turbidimeters are less susceptible than visible light turbidimeters to interference caused by the color imparted by dissolved substances commonly found in natural water samples. This also means, however, that incandescent light turbidimeters (which are typically filtered to produce light over the range of 400-600 nm) can better measure turbidity from smaller clay particles than near-infrared turbidimeters can – a 60nm clay particle, for example, will scatter roughly 8.75 times less light with an 860nm light source than with a 500nm light source. For the monitoring of natural water bodies, the choice of light source often makes small difference in practice but can be significant in the measurement of very low turbidities, where ultra-precise measurements are needed, or where a high concentration of nanoparticles may be expected (Sadar 1998).

Commercial turbidimeters employ precision optics and electronics to detect turbidity readings as low as 0.02 NTU in samples of varying color and chemical composition (in accordance with certification protocol [EPA 1993]). Handheld commercial models, capable of analyzing a sample manually loaded in a quartz cuvette, typically cost upwards of $600. Automated (inline) turbidimeters, capable of intermittently analyzing samples from a moving column of water and relaying results to a computer or data-logger, typically cost upwards of $2,000. In many areas of the world, communities may not have the fiscal resources to purchase and maintain devices with costs this high, or water treatment monitoring may not be a sufficient priority to justify this expense.

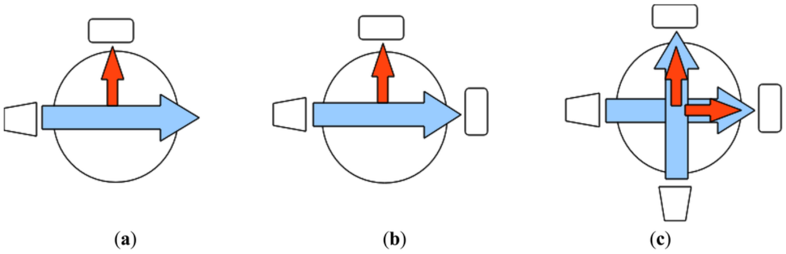

Figure 2.1. Common turbidimeter design patterns: (a) single-beam, (b) ratio, (c) modulated four-beam. Components: light source (trapezoid), liquid sample (circle), detector (rectangle), transmitted light (large arrow), scattered light (small arrow).

2.3 National regulations and international guidelines for the treatment and monitoring of turbidity in drinking water

EPA

Turbidity standards for the United States are set out by the EPA in section 40 of the Code of Federal Regulations (hereafter 40 CFR). The National Primary Drinking Water Regulations (hereafter NPDWR, found in 40 CFR part 141) cover surface water and ground water separately with respect to turbidity. For treatment of surface water, or of groundwater that is "under the influence of" (mixed to some degree with) surface water, the following turbidity standard applies:

> "For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95 percent of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs." (NPDWR 2008).

It should be noted that this is a simplified view of turbidity monitoring in the US. American turbidity standards, and water quality standards in general, can be quite nuanced and complex, as the federal government defers implementation of most aspects of federal water law to state “primacy agencies”, which act under the authority of the state governor as the top environmental authority in the state (and which report data quarterly back to the federal government). When a federal water law is passed, states can implement the legislation with whatever language they see fit, so long as that legislation includes all aspects of the federal law. To abstract from this situation, it is sufficient for this document to note that when surface water – or groundwater with potential influence from surface water – is being treated, smaller water treatment systems in America may be able to take turbidity grab samples throughout the day using a handheld turbidimeter. For larger systems, which may be required to monitor turbidity at multiple locations in the treatment plant multiple times per hour, it may be economically competitive (and perhaps a practical necessity) to purchase and install an automated, inline turbidity monitoring system.

European Commission

The European Commission (EC) sets out water quality requirements for European Union (EU) member states in a document titled “COUNCIL DIRECTIVE 98/83/EC of 3 November 1998 on the quality of water intended for human consumption" (Ljujic & Sundac 1998). In contrast to EPA regulations, the EC directive is relatively lax in turbidity standards, perhaps owing to the need to harmonize the formerly independent water treatment frameworks of multiple member states. In Part C – Indicator parameters – the document only requires that a water’s turbidity level is “Acceptable to consumers and presents no abnormal change”, noting “In the case of surface water treatment, Member States should strive for a parametric value not exceeding 1,0 NTU (nephelometric turbidity units) in the water ex [sic] treatment works”.

Selected Low- and Middle-Income Countries

Turbidity standards vary considerably from nation to nation, (though few if any nations have stricter turbidity standards than the United States). Table 2.1 gives the permissible turbidity limits for drinking water in several countries for comparison.

Table 2.1. Turbidity standards (as maximum permissible values, NTU) for various countries.

State	**Turbidity standard (NTU)**	**Regulation source**
India	5	BIS 2012
China[A]	1-5	MHC 2006
Honduras	5	RADWS 2005
Brazil	1	MSB 2004
Argentina	3	MSAAS 1994
Peru	5	MSP 2010
Chile[B]	2	INN 2004
Ghana	5	MWRWH 2015
Europe	1	Ljujic & Sundac 1998
Australia	0.5	NHMRC 2011

Notes:

A. For large and urban drinking water systems, China sets a target of 1 NTU and an upper acceptable limit of 3 NTU. For small and rural systems, the target is 3 NTU and an upper acceptable limit of 5 NTU.

B. While the average turbidity value must be 2 NTU or under to meet Chilean law, samples of up to 20 NTU are permissible so long as they are not from consecutive days.

World Health Organization (WHO)

The WHO has published water quality recommendations since at least 1958. Particular attention is given here to the lengthy history of WHO recommendations for turbidity standards, given the international scope of these recommendations and the likelihood that they have influenced the turbidity standards of several countries (Pinto et al. 2012).

In all three editions of the WHO International Standards for Drinking-Water turbidity guidelines are given as “5 units permissible, 25 units excessive” (WHO 1958, WHO 1963, WHO 1970). The advice of the WHO’s Surveillance of Drinking-Water Quality however was more exacting:

> "The objective should be to produce water with a turbidity of less than 0.5 Jackson unit (JTU; defined in ASTM 2000). In well operated plants turbidity will not normally exceed 1.0 JTU" (WHO 1976).

The WHO’s Guidelines for Drinking-Water Quality lists a turbidity standard of 5 NTU (“preferably”), advising a goal of less than 1 NTU just prior to disinfection in its first edition (WHO 1984). The second edition tightened this recommendation somewhat:

> "To produce water with negligible virus risk...the median value of turbidity before terminal disinfection must not exceed 1 nephelometric turbidity unit (NTU) and must not exceed 5 NTU in single samples” (WHO 1993).

The third edition of the guidelines seems perhaps over-ambitious, stating that:

> "No health-based guideline value for turbidity has been proposed; ideally, however, median turbidity should be below 0.1 NTU for effective disinfection" (WHO 2004).

By the fourth edition (WHO 2017a), which at the time of this writing has recently incorporated a first addendum, guidance on turbidity levels had relaxed somewhat:

> “Large municipal supplies should consistently produce water with no visible turbidity (and should be able to achieve 0.5 NTU before disinfection at all times and average 0.2 NTU or

> less). However, small supplies, particularly those where resources are limited, may not be able to achieve such levels."

Referring separately to disinfection with chlorine, and with UV light:

> "[T]urbidity should be kept below 1 NTU to support effective disinfection. Where this is not practical, the aim should be to keep turbidities below 5 NTU".

An enduring element of WHO recommendations since 1984 is that, prior to disinfection, drinking water should have a turbidity of 1 NTU or lower, which may be an acknowledgement of the widely cited work of LeChevallier and others on the influence of turbidity on disinfection efficiency in drinking water (LeChevallier at al. 1981).

2.4 National regulations and international guidelines for the development of turbidimeters

At present, nephelometry standards defined and/or recognized by the EPA and ISO appear to be the only national or international standards which specify design standards for turbidimeters. No other national or international standards dictating the functional parameters of turbidimeters could be found, and WHO guidelines are silent on the general topic of water quality monitoring device construction.

2.4.1 EPA

EPA Method 180.1 is a freely available nephelometry standard promulgated by the EPA. It is the most generic and widely referenced of seven nephelometric methods approved by US federal law for regulatory compliance use in drinking water treatment plants and laboratories; the other six being GLI Method 2, Standard Method 2130 B-2011, ASTM D1889-00, USGS Method I-3860, Mitchell Method M5331, Mitchell Method M5271, and Orion Method AQ4500 (NPDWR 2008). The last four of these methods are manufacturer-specific and prescribe the use of a specific model or models of commercially manufactured turbidimeter. Standard Method 2130B and ASTM D1889-00 use the same device requirements language for electronic turbidimeters as EPA Method 180.1 (listed below; ASTM D1889-00 also details device requirements for older equipment such as non-electronic slit turbidimeters). Finally, the turbidimeter design requirements in GLI Method 2 effectively stipulate a modulated four-beam version of the single-beam nephelometric apparatus specified by International Organization for Standardization method ISO 7027 (see below) for use in waters with degrees of natural color (Wilde & Radke 2001). At least three of these standards – the Orion method and the two Mitchell methods – were approved under the EPA Alternate Test Program (ATP), which provides for the evaluation and possible approval of non-standard measurement techniques, so long as these novel techniques are capable of meeting requirements set out in the standard measurement technique (Walker 2017). From here forward, EPA Method 180.1 is the sole focus when discussing American turbidimeter design regulations.

The key device design requirements specified in EPA Method 180.1 are given in Section 6:

> "6.2.1 Light source: Tungsten lamp operated at a color temperature between 2200-3000 degrees K."
>
> "6.2.2 Distance traversed by incident light and scattered light within the sample tube: Total not to exceed 10 cm."
>
> "6.2.3 Detector: Centered at 90 degrees to the incident light path and not to exceed +/- 30 degrees from 90 degrees. The detector, and filter system if used, shall have a spectral peak response between 400 nm and 600 nm."
>
> "6.3 The sensitivity of the instrument should permit detection of a turbidity difference of 0.02 NTU or less in waters having turbidities less than 1 unit. The instrument should measure from 0-40 units turbidity. Several ranges may be necessary to obtain both adequate

> coverage and sufficient sensitivity for low turbidities." (EPA 1993)

A minimum level of detection of 0.02 NTU can be inferred. The range of 0-40 NTU is considered the acceptable nephelometric range for EPA Method 180.1, as noted in the Procedure section:

> "11.2: Turbidities exceeding 40 units: Dilute the sample with one or more volumes of turbidity-free water until the turbidity falls below 40 units." (EPA 1993)

It should be noted that this regulation thus presumes ready access to turbidity-free water (which must be distilled or multiply filtered with laboratory-grade equipment). Other relevant requirements in EPA Method 180.1 (directly quoted) include:

> "6.1 The turbidimeter should be designed so that little stray light reaches the detector in the absence of turbidity and should be free from significant drift after a short warm-up period."

> "6.4 The sample tubes to be used with the available instrument must be of clear, colorless glass or plastic. They should be kept scrupulously clean, both inside and out, and discarded when they become scratched or etched." (EPA 1993)

Regarding calibration standards, the method states:

> "2.1.1 Formazin polymer is used as a primary turbidity suspension for water because it is more reproducible than other types of standards previously used for turbidity analysis."

> “3.8 Secondary Calibration Standards (SCAL) -- Commercially prepared, stabilized sealed liquid or gel turbidity standards calibrated against properly prepared and diluted formazin or styrene divinylbenzene polymers.”
>
> “5.3 Hydrazine Sulfate (Section 7.2.1) is a carcinogen. It is highly toxic and may be fatal if inhaled, swallowed, or absorbed through the skin. Formazin can contain residual hydrazine sulfate. Proper protection should be employed.”
>
> “7.3.1 A new stock standard [formazin] suspension (Section 7.2) should be prepared each month. Primary [formazin] calibration standards (Section 7.3) should be prepared daily by dilution of the stock standard suspension.”
>
> “7.6 Secondary standards may be acceptable as a daily calibration check, but must be monitored on a routine basis for deterioration and replaced as required.” (EPA 1993)

Thus, in addition to ready access to turbidity-free water, this standard presumes at least monthly access to formazin and the facilities in which to keep it.

2.4.2 International Organization for Standardization (ISO)

ISO 7027:2016 is a closed-access nephelometry standard developed by the International Organization for Standardization (ISO 2016). The business model of the ISO centers on selling access to their standards to fund research to establish new standards. Customers must purchase a copy of a given standard to read it.

The key device design requirements specified in ISO 7027 are given in Subsection 5.3.1.1:

> "(a) the spectral bandwidth of the incident radiation shall be contained in the range of 830 nm to 890 nm."
>
> "(b) there shall be no divergence from parallelism of the incident radiation, and any convergence shall not exceed 1.5°."
>
> "(c) the measuring angle, θ, between the optical axis of the incident radiation and that of the diffused radiation shall be 90° ± 2.5°;"
>
> "(d) the aperture angle should be between 20° and 30° in the water sample." (ISO 2016)

Perhaps the most striking aspect of ISO 7027 is the lack of language stipulating accuracy, precision, or minimum level of detection (in contrast to EPA Method 180.1). Major manufacturers that produce ISO 7027-conformant turbidimeters, such as HF Scientific (Fort Meters, FL, USA) and Hach (Loveland, CO, USA), outfit their devices to measure as low as 0.02 NTU and measure with 2-3% accuracy. In principle there is nothing preventing a company from designing a turbidimeter that can only measure above 5 NTU and with an accuracy of +/- 100% and having it certified ISO 7027-compliant. Of further potential concern is the fact that the standard does not stipulate calibration requirements beyond following the manufacturer's instructions (Section 5.3.2), and no maximum interval between recalibrations is given.

ISO 7027 does have language regarding the primary standard formazin, and secondary standards made of pre-diluted formazin, that is comparable to that of EPA Method 180.1. One key difference is that ISO 7027 explicitly defines a maximum period – six months – between inspections (via comparison with primary formazin standards) to ensure that secondary calibration standards, used for routine turbidimeter calibration checks, match their stated values. (This recalibration timeframe applies to the standards, but not the conformant turbidimeter itself.) Thus, this standard presumes access to freshly prepared formazin at least annually (Section 5.2.2) along with facilities for its storage and, like the EPA Method 180.1, presumes access to turbidity-free dilution water.

2.5 Commercial development of turbidimeters

The regulatory stipulations detailed in Section 2.4 appear to have helped shape a global market for commercial turbidimeters with the following nuances;

1. EPA regulations – targeted to the treatment regulations of developed countries – stipulate that commercial turbidimeters must be able to make measure very low turbidities quite accurately. This is more monitoring power than what is needed for monitoring compliance with the main WHO turbidity guideline of 1.0 NTU or less prior to disinfection. ISO regulations, conversely, stipulate exceedingly little about the expected performance of a conformant turbidimeter – to the point that a willfully poor turbidimeter could be certified for compliance. Likely in response to demands of developed economies, however, the market for both classes of nephelometric turbidimeter continues to be dominated by high-performing, high-priced devices.

2. For some common parameters such as pH and chlorine residual there are relatively inexpensive single-use tests based around colorimetric indicators in the form of test strips or powder sachets. These tools are well-suited to the intermittent monitoring needs of, say, the typical swimming pool owner, however the cumulative cost of a drinking water quality monitoring program based around these "cheap" single-use tests can add up quickly. For turbidity, as noted previously, no affordable single-use tests exist.

3. Development and marketing of commercial turbidimeters is centered in developed countries, whose water treatment plants and water quality laboratories can more readily absorb equipment costs stipulated by drinking water regulations.

4. Development is more closed-source than the auto industry – for major turbidimeter manufacturers, even maintenance must be conducted at a limited network of service centers directly contracted by the manufacturer (confirmed by email with representatives of Hach, HF Scientific, and Hanna Instruments [Woonsocket, RI, USA]). While nothing in the EPA and ISO regulations specifically forbid third-party maintenance of commercial turbidimeters, major manufacturers appear to defend their market position through IP protection and do not publish their turbidimeter specifications. Thus, for non-obvious issues, before a commercial turbidimeter could be serviced by a third party it would have to be reverse engineered (which could damage the device and might bring risks of IP infringement). Perhaps in part because of this highly closed-source manufacturing model, the major commercial turbidimeter manufacturers have limited global distribution and repair networks.

Given the high costs of commercial turbidimeters (typically \$600 - \$1500 for a handheld model, and \$2000+ for an inline model) one would likely presume that the technology inside them is commensurately expensive. It is of course difficult to judge the cost of parts and labor by the sale price of a finished product; logically this should be especially difficult when a regulatory structure compels a set of customers to make purchases from a limited selection of options and effectively creates a semi-captive market. To better understand the parts and labor costs of commercial handheld turbidimeters, a broken MicroTPI turbidimeter (common handheld model, produced by HF Scientific) was subjected to a "teardown" – a disassembly and internal parts identification. The parts and labor costs of the MicroTPI were estimated at \$266.07 for a device that typically retails for roughly \$800. (Estimation procedure is detailed in Appendix D.) It is worth noting that, judging from several aspects of the design of the circuitry, it seems likely that the device was designed at least 10 years ago. Neither the manufacturer HF Scientific nor its parent company Watts Water Technologies seems to hold any active patents for turbidimetry or nephelometry (judging from a thorough examination of the Google patent records repository), and while the MicroTPI is a well-built machine there appears to be nothing unexpected or innovative in the circuitry it contains or the detection methodology it employs. The branding, advertising, and other various attendant costs of running a major commercial enterprise that manufactures closed-source scientific and engineering equipment are no doubt considerable, though, and are not estimated here.

5. Business costs would logically be increased if distribution, service, and repair networks were globally expanded for closed-platform water quality monitoring devices such as handheld turbidimeters to a sufficient degree to reach a large but spatially diffuse market of customers in low-resource settings (LRS). For water quality monitoring equipment such as inline chlorine monitors, jar testers, and of course turbidimeters, it also seems likely that low customer volume (relative to, say, common household goods or cell phones) drives up operating costs when coupled with a globally distributed customer base.

6. Water quality monitor purchasing costs for customers in many LRS are increased by the need to purchase finished electronic goods from a foreign country (which may incur import tariffs and duties), which again are often designed for monitoring turbidity (or other analytes) at levels far in advance of the accuracy and detection limit requirements of local regulations, and/or at levels far better than what can be realistically achieved by the treatment process to be monitored.

7. Maintenance costs for closed-platform turbidimeters and other water quality monitoring devices are a potential impediment to monitoring programs, for customers who do not have the means or geographical proximity to afford to ship devices in need of repair to the nearest manufacturer-approved repair facility.

8. The need to ship devices to regional repair centers has a knock-on effect on the costs and/or sustainability of monitoring programs, as monitoring agents must either purchase monitoring

equipment in excess of what is strictly needed or risk disruption to regular monitoring activities during device shipping and maintenance periods.

9. Data connectivity, and even data storage, tend to be treated by commercial manufacturers as premium features for turbidimeters and other handheld water quality monitoring devices (judging from the limited availability, and cost premiums where available, of data storage and transmission features on handheld water quality monitoring devices from major manufacturers). This increases the time, salary and equipment costs that must be invested in clerical activities to record and communicate datasets obtained with non-premium commercial water quality monitoring devices.

10. There seems to be little motivation for device manufacturers to address these problems systematically. Relative to the current market situation, it is doubtful that a global expansion of distribution and repair center networks and lowering of prices on turbidimeters to meet the requirements of a large but diffuse and impoverished market segment in LRS markets would be viewed as a sound course of action.

11. As mentioned before, there seems to be no legal room for the EPA to specify such a “second-tier” nephelometry standard, as this would violate the EPA's Alternate Test Procedure guidelines, which forbid the approval of water quality standards that are less stringent (e.g. in accuracy and resolution) than what the standard EPA method demands (NPDWR 2008). The motivating factor for this stipulation is not stated but is presumably the desire to be egalitarian. As the EPA notes of its Drinking Water Alternate Test Procedure Program, which facilitates the evaluation of new or modified testing standards for the detection of regulated contaminants: “There is no tiering of methods or validation studies for drinking water ATPs [Alternate Test Procedures]. All test methods used to measure contaminants in drinking water must be approved for nationwide use in all matrices (ground water and surface water source waters).” (EPA 2017). Requiring that all EPA-approved test procedures for contaminant detection meet strict and uniform guidelines ensures that

the nation's network of drinking water laboratories cannot employ tiered pricing strategies and impose an economic gradient on water quality monitoring; nor can drinking water treatment providers cut corners by selectively employing less rigorous monitoring protocols in daily water treatment operations.

It is within the purview of the ISO to either revise their current nephelometry standard or establish a new nephelometry standard with more specific language on performance targets and design constraints. Given that the ISO turbidity standard has had roughly the same language since 1990, though, this may be unlikely. It is also questionable what utility a new or revised ISO standard would have for major manufacturers of closed-source turbidimeters, unless the economics of global distribution and repair of a low-cost version of an electronic good with relatively low customer demand can be made more appealing (i.e. through the development or enforcement of regulatory mechanisms in multiple developing countries to compel usage). Furthermore, for individual small-scale and open-source device manufacturers, who would likely have much smaller geographical reach and market volume than the current major turbidimeter manufacturers, the cost of purchasing access to – and certification of conformance with – a new or revised ISO nephelometry standard might be a severe disincentive for adoption.

12. The WHO Water-Quality Guidelines could be an appropriate place to include standards language for monitoring devices that are capable of analyte observation at WHO target levels. Judging from the WHO's short note "Rolling revision of the Guidelines for drinking-water quality: Programme of work", however, this does not seem to be a current priority (WHO 2017b).

A key takeaway message here is that regulations and economics would appear to impact monitoring activities in part by modulating the commercial development and distribution of monitoring devices (which again are a necessity for useful water quality monitoring efforts). It seems that globally we have a large and persistently unmet need for water quality monitoring devices that are more affordable than what the market currently offers, and that can be repaired in LMIC's without expensive and lengthy shipping processes to for maintenance at manufacturer-certified repair centers that may be hundreds or thousands of miles away.

If we were to summarize some general market and maintenance needs for basic turbidimeters in a given LRS community – particularly if we were dealing with smaller manufacturers than the likes of Hach and HF Scientific – we would likely want a reliable turbidimeter that could be:

Constructed in or near the community – or perhaps at least within a shared cultural and economic zone, to limit tariffs and shipping costs and perhaps improve multilingual support.

Afforded by the community – the turbidimeter must be suited to the financial means of a community.

Maintained in or near the community – perhaps at a local cell phone store, or at least within a distance that permits quick turnaround and low shipping charges.

Operated in the community – the community must have the resources (personnel, infrastructure) to use the turbidimeter.

So, if commercial turbidimeters are overpriced and overpowered for LRS monitoring, with import tariffs and onerous offsite maintenance demands, what alternatives do we have? With apologies for taking the convenience of a clumsy acronym from the bolded words above, how can we satisfy this "CAMO" principle?

2.6 Open-source development of turbidimeters: opportunities and challenges

Open-source technology is, in a simple sense, technology that may be freely shared and adapted. The development of modern open-source technology began with open-source software, such as the GNU operating system (Bretthauer 2002). Several open-source software projects have become industry standards, such as the Linux operating system (LF 2017) and Apache HTTP Server (ASF 2017). The Free Software Foundation, a non-profit connected to the GNU operating system, identifies four freedoms it deems essential for open-source software, including the freedom to (1) use a piece of software however desired, (2) study how the software works, (3) share original copies of the software with others, and (4) share modified copies of the software with others (FSF 2017). Modern open-source hardware has a shorter history than open-source software, though there have been recent open-source hardware projects such as the Arduino microcontroller (Arduino 2017) and the RepRap 3D printer (RepRap 2017) that have garnered large and global user communities. Organizations and individuals have articulated open-source principles in legally binding licenses to define and defend open-source technology, and such open-source licenses have proliferated to address nuances in the desire to share technology (e.g. sharing but not allowing commercialization of derivative works) and issues arising from the complexity of technology (e.g. open-source software that makes use of proprietary compiled libraries). In principle, then, open-source technology could certainly help form the basis for hardware that meets the CAMO principle above.

In recent years, many interesting examples of open-source tools for science, medicine, and engineering have been documented in peer-reviewed journals. (There are far too many to list here; Pearce (2012) and Dryden et al (2017) provide overviews.) A rich body of peer-reviewed literature has served to document recent novel turbidimeter designs. Researchers have developed devices for diverse applications such as quality control for the food industry (Dongare et al. 2013, Novo et al. 2013), field measurements of suspended solids (Bilro et al. 2011, Orwin & Smart 2005), and dynamic operation of small appliances (Smith et al. 1996, Taylor & Bull 1998). Others have explored low-cost sensor designs (Bilro et al. 2012, Omar & MatJafri 2011) and incorporated wireless connectivity for distributed real-time turbidity monitoring (Lambrou et al. 2010). Many researchers have developed or reviewed devices for low-cost monitoring of turbidity in surface water and drinking water [Lambrou et al. 2010, Liu & Xu 2009, Pereira et al. 2004, Garcia et al.

2007, Ranasinghe & Ariyaratne 2012, Sun et al. 2006, Tai et al. 2012, Wijenayake & Alahakoon 2012, Wang et al. 2015, Bardaji et al. 2016, Murphy et al. 2105, Naykki et al. 2014, Alvarenga et al. 2017, Hussain et al. 2016, Bhavsar & Kanjalkar 2016]. There have also been collaborative public turbidimeter design efforts, such as the Public Lab Riffle Turbidimeter (Public Lab 2015), and projects such as the TurbidGNUSB and BabyTurbiduino listed by the open-source design website Hackteria (Hackteria 2016).

Unfortunately, it does not appear that any of these devices are field ready. None are on the market. Few appear to have been developed beyond the prototype stage, nor do many of the efforts listed above appear to have publicly available designs and plans so that development and marketing could be completed by an outside party. For those projects that are not explicitly noted as open-source, it is not known whether they are being further developed privately. Finally, and perhaps most importantly, very few of the recently published turbidimeter designs above state the standards they are attempting to meet with their device, and almost none offer testing data from an independent party to verify claims of device performance. Without independent testing, and no history of successful use by customers, it is naïve to assume adequate performance for turbidity monitoring in LRS.

What would be required of effective open-source designs for water quality monitoring devices that can be manufactured in a globally distributed manner?

The Open Source Hardware Association (OSHWA) provides a 12-point definition of open-source hardware (OSHWA 2017), which forms the basis for their open-source license and certification process, though they do not specify guidelines for the development of open-source hardware projects. Pearce (2014) and Gibb et al. (2014) discuss general requirements of open-source development at length, which emerge from the inherent need in an open-source environment to exchange not only devices themselves (which could be given or sold), but also the “source” files underlying the creation of these devices (which must be freely available and freely usable). For a typical hardware development project – for the sake of relevance we will assume a project that involves electronics – these source files would include:

1. Physical design files, which represent physical objects that are part of the hardware. These may be as simple as drawings, but would more usefully be electronic spatial representations of the objects (such as Computer-Aided Drafting [CAD] files) – especially if the objects can be manufactured in an automated or semi-automated fashion.
2. Circuit board design files, which encode the layout of the electronic hardware. These typically consist of a schematic (which is a logical representation of the connections between electrical components which a circuit board will provide) and layout (which is a spatial representation of how the components and connections outlined in the schematic will fit onto an actual circuit board). Additionally, footprint files (which define the physical shape and often the logical function of the components that will be soldered to the circuit board) are required. From these, Computer-Aided Manufacturing (CAM) job files can be produced which are used by manufacturers to produce circuit boards (or alternately, circuit boards can be etched from sheets of copper-clad fiberglass for relatively little time and money).
3. Bill of Materials (BOM), which lists the electrical and non-electrical components needed to build a piece of hardware, where they may be found or purchased, and their unit cost.
4. Datasheets for purchased items like electrical components which may have detailed instructions for use and collections of publicly available testing data to demonstrate their utility.
5. Software and firmware; the latter referring to low-level computer code that below the level of an operating system, which run any microcontrollers or microprocessors and connected peripherals in the hardware.
6. Toolchain: a description of the full set of tools and procedures required to produce the piece of hardware from the initial ingredients.

Additional key items of a successful open-source hardware development effort identified by Pearce and Gibb et al. include:

7. Iteration: developing a product progressively with testing and evaluation between iterations.
8. Feedback, from other developers and from hardware users – which implies having source files and documentation easily available.
9. Supplementary documentation: photos, videos and anything else that helps provide copious, multi-modal documentation of the development process to help others reproduce the hardware development effort.
10. Licensing, to clarify the terms of use of the project (which may involve separate licenses for, e.g., hardware and software components).

As a process for the transparent and collaborative creation of physical tools, open-source hardware development seems to hold significant potential for global water quality monitoring, including turbidity monitoring. There are currently no open-source turbidimeters on the market, and it seems that nothing in the peer-reviewed literature or publicly available on the web is ready for large-scale manufacturing and deployment. As nations work to improve the quality of the drinking water that their citizens consume, and microelectronics get smaller, more powerful, more connected, and easier to assemble and program, it would seem likely that product development efforts from parties other than the current major manufacturers will play an increasingly important role in fulfilling the global need for water quality monitoring devices including turbidimeters.

Open-source development efforts have at least the potential to play a positive and transparent part in the improvement of global water quality monitoring. Whatever development ethos drives the next expansion of turbidimeter markets, however, more exacting turbidimeter design requirements would seem prudent.

2.7 Clarity and completeness of standards for turbidimeter development

As discussed above, commercial turbidimeters on the global market are designed to specifications codified by the EPA or the ISO, and are built and distributed as closed-source devices by large companies serving a global market that is economically dominated by highly developed regions such as the US and Europe. The EPA and ISO standards may be in certain ways over-specific or incomplete, but they are nevertheless the product of expert consultation. It would be presumptive and unwise to abandon existing turbidity treatment and monitoring standards completely and create a new standard simply because it is more conducive to open-source device development or globally distributed manufacturing. There is merit, however, in expounding device design requirements that are absent from the current language of the EPA and ISO standards, which would be important details of a potential open-source turbidimeter development standard.

The turbidimeter design requirements for EPA and ISO are given in Section 2.4. ISO requirements governing the selection and application of a candidate LED for a nephelometric turbidimeter, to briefly restate, include the dominant wavelength, the spectral bandwidth, angle of emitted radiation, angle of measurement between light emitter and light detector, and aperture angle of the water sample. Conspicuously absent from this list, and from the standard entirely, is any discussion or requirement concerning the actual brightness of the LED. As silicon devices, LEDs invariably demonstrate an inverse correlation of brightness and temperature (Floyd & Buchla 2002). This may be compensated for directly (e.g. by increasing the current supplied to the LED or by heating the LED), or indirectly (e.g. by correcting for decreased brightness in software calculations) but must be addressed if a photometric device like a turbidimeter is to perform correctly outside of a narrow ambient temperature band (Johnson 2003).

EPA Method 180.1 and ISO 7027 are method-centric standards – that is, they focus on proper use of a well-made turbidimeter, rather than focusing on how a turbidimeter should be made. It is understandable that ISO 7027 does not specify a particular method or set of methods for LED temperature compensation; technical innovation – and thus competitive advantage and market share – may easily be constrained by over-prescriptive regulation. However, the fact that this issue is unaddressed entirely in the design requirements may confound non-commercial turbidimeter development efforts by presenting an under-specified target – and indeed, almost none of the academic or open-source turbidimeter designs given in Section 2.6 include measures for temperature compensation. This suggests the potential utility of supplementary documentation to guide the development of novel turbidimeters produced by non-commercial effort.

A more troubling issue with the ISO 7027 standard is the lack of temperature as a calibration variable. While the standard contains detailed sections on the temperature requirements during the standard synthesis of formazin, temperature as a potential confounder of the measurement of a calibrated turbidimeter is never discussed (ISO 2016). This is a potential issue for turbidimeters that conform to EPA Method 180.1 as well, for even though tungsten lamps (specified as the light source in that standard) have relatively low temperature coefficients, a modern electronic turbidimeter is likely to contain many components (such as resistors and operational amplifiers) with potentially significant temperature coefficients. Stability of a turbidimeter's operating voltage is another potentially critical operational parameter that is likewise not discussed in either standard. Subtler design issues, such as non-linearities in the performance of certain integrated circuits (e.g. analog-to-digital converters) over the turbidity measurement range, may also be important for many turbidimeters (Johnson 2003). These issues suggest the utility not only of guidance documentation for open-source and non-commercial development teams, but also of additional regulatory language targeting commercial turbidimeter development.

As long as commercial turbidimeters from major manufacturers are too expensive to be afforded by a given community, or too expensive to ship for maintenance from a given region, then the relevant turbidity monitoring regulations in that area of need will be effectively unenforceable. It is in these areas that open-source and small-scale commercial monitoring technologies can flourish, even alongside commercial products with more stringent performance demands. Without standards for water quality monitoring devices that actually address key design variables, however, open-source design teams may inadvertently produce unacceptable products that, e.g., work reliably in a climate-controlled laboratory but fall out of calibration readily in field conditions. Worse, profit-seeking commercial efforts utilizing closed-source technology may exploit the lack of a functioning market for effective devices in order to profit from the sale of inadequate or ineffective devices. The lack of device-centric language in current EPA and ISO turbidimetry and nephelometry standards addressing crucial operational parameters like voltage and temperature constitutes a hole in the regulatory fabric.

This situation is potentially made worse by the fact that neither EPA Method 180.1 nor ISO 7027 contain a certification process for establishing compliance with the method – verification of method conformance is effectively up to the end user to determine. For the ISO standard, this requires paying a qualified third party for certification services – however, as the standard does not forbid spurious association in any way, one could instead simply promote their turbidimeter as having been “designed to meet ISO 7027” instead of “ISO 7027 certified”. The EPA on the other hand does not require certification to verify that turbidimeters conform to EPA Method 180.1. Regulated entities under the National Primary Drinking Water Regulations, such as water treatment plants and testing laboratories, must conduct due diligence to ensure that the turbidimeters they purchase are in fact able to comply with an EPA-approved nephelometry method (Walker 2017). That is to say, if a manufacturer is convinced that a turbidimeter they have developed is conformant with EPA Method 180.1, they can simply state that this is so, and it is then up to that supplier’s customers to choose whether to take a chance on the technology. In a developed economy where regulated entities have a government-enforced obligation to purchase well-functioning monitoring equipment, and have guidance from a state agency in selecting such equipment, this system is adequate. In such situations customers are more likely to have market choices and be able to make informed decisions, and the need for manufacturers to maintain good reputations is paramount. This is, presumably, part of the reason that Hach makes turbidimeters that perform well across temperature and operating voltage ranges even though the EPA turbidity standard doesn't discuss or test these variables – it matters to their bottom line that their products work well and meet their customers' needs.

If people lack the means to participate in the market for monitoring equipment or entice equipment producers to innovate, and regulatory enforcement is lax, self-certification systems is likely inadequate. As an example, the WGZ-1B Portable Turbidimeter by Hanchen Instruments, one of a few very models of commercial turbidimeter available for under \$600, has been available on Amazon for around a year at the time of this writing (Amazon 2017). The plainly packaged device, which is available from one third-party seller for roughly \$200 dollars, is "designed to meet ISO 7027" and is not "ISO 7027 certified". Given the extremely limited device design specifications in ISO 7027, however, it is not difficult to imagine that the WGZ-1B might indeed be conformant to the standard. The limited documentation available on the device lists a precision of 8% or 2.5% F.S., the latter of which is "full-scale" error (Lipták 2013). Interpreting these specifications charitably yields a precision over the device's operating ranges of +/- 0.5 to 1.6 NTU for 0-20 NTU and +/- 5 to 16 NTU for 20-200 NTU. Assuming the device does what it claims, this may be acceptable for basic monitoring – though at a higher price than should be expected for relatively coarse turbidity monitoring performance. A concern, however, is that the manufacturer Hanchen Instruments seems to have no international repair network, device performance datasets to request, web page, or even contact info. This is not what we should want from a low-cost turbidimeter market.

Where societies seem willing to let the poor make do with less, it is possible that the current EPA and ISO turbidity standards could inadvertently facilitate the marketing of cheap, inadequate turbidimeters. If customers lack the financial means or the power of choice in their local market, or otherwise lack an effective channel to demand quality of the products they can afford, then government standards may be crucial to ensuring that the marketplace offers useful goods and services. This is to say, if we want cheap, *adequate* turbidimeters, targeted standards and guidance need to be in place to help achieve this. This would seem to require open and freely available design standards, which:

1. Specify design and especially reporting requirements;
2. Ensure that key variables for useful device operation are addressed in design specifications and, wherever useful, in testing procedures;
3. Do not assume that a government agency will verify that monitoring devices meet design requirements, nor resolve ambiguities in monitoring device design specifications;
4. "Harden" design specifications against misuse, and include verification procedures (such as requiring publicly available device performance data from multiple external testing partners);
5. Require communications and data-sharing capabilities;
6. Above all, spur the development of devices that can be built, afforded, and maintained in-country in LRS, designed for the specific monitoring context to which they are marketed. In other words, turbidimeters that fit the CAMO principle.

2.8 Conceptual and contextual issues in existing standards for water quality monitoring device development

The previous section noted issues central to the development of turbidimeters that are not addressed in the process-centric EPA and ISO standards and which could prove problematic for consumers and regulators alike when dealing with devices produced by smaller open-source and closed-source manufacturers. As global equity in water quality monitoring seems unlikely to emerge from a market composed only of powerful, expensive monitoring devices designed by a handful of major manufacturers for the needs of the most economically competitive customers, regulation and guidance for low-cost monitoring outside of a well-appointed laboratory and in the absence of strong state regulation should be considered. That is, we should consider the context and practice, not just the protocol, of water quality monitoring.

To start, let us then consider the turbidimeter per se as a contextually situated monitoring device, rather than as a commercially manufactured black box that does or does not meet a device performance standard. At the most basic, we would consider a formal ontology of the turbidimeter – the essential constituents of the device, and the processes of its measurement technique. Following work conducted by Kuhn (2007) and Borgo & Vieu (2009) on the ontological issues of environmental observation and technical systems, and employing the DOLCE ontology framework (Masolo et al. 2003), the process of using a turbidimeter may be examined thusly:

An aqueous sample in a cuvette, which constitutes an "Observable", provides a proxy for two "Endurants" (elements that continuously exists in time) – the body of water being sampled, and a collocated load of sediment. It also contains a "Perdurant" (an element that occurs in time) – the suspended sediment load in the sample of the body of water at the time of measurement (Masolo et al. 2003). As Kuhn (2007) notes, in environmental observation the distinction between endurants and perdurants is largely a matter of the observer's timeframe of interest. For example, for typical monitoring purposes, we would conceptualize the water in the cuvette as belonging to a body of water, rather than as a tiny piece of the global evapotranspiration cycle. However, we typically would be concerned about the daily or even hourly variation of turbidity levels in that body of water (and if we are being thorough in our sampling, we would homogenize the water sample in the cuvette by repeatedly inverting or shaking the cuvette and then letting it stand briefly, to maximize repeatability of replicate measurements). The turbidimeter, which acts as the “Observer”, adds a “Stimulus” to the Observable by passing a beam of light through the aqueous sample. This Stimulus inheres a “Quality” in the Perdurant element (the light scattered by the suspended sediment in the cuvette). The turbidimeter, under the operation and influence of the human user, observes a small portion of the signal from the Quality, which acts as a proxy signal that is causally linked to the Perdurant. The turbidimeter completes an “Observation” process by observing the partial signal of the Quality and producing an analog “Impression” (an electric current) at the light sensor which the turbidimeter then converts into an “Expression”, a discrete observation value, by digitizing the Impression either at the light sensor (in the case of a light-to-frequency sensor) or via an analog-to-digital converter (in the case of light-to-voltage or light-to-current sensor) and interpolating to a previously stored calibration curve representing a best-fit line between reference Observations.

Adopting an ontological framework for examining nephelometry raises questions that are addressed by EPA and ISO regulations (such as “What is the timeframe of interest of the Perdurant element?”), as well as questions that perhaps ought to be addressed (such as “Are there external conditions [such as ambient temperature variation] that may affect the production of an Impression from the Observation of a Quality?”). In general, it seems self-evident that exploring the concepts and relations involved in the performance of a monitoring activity raises epistemological issues more readily than viewing a monitoring activity through the lens of a procedural regulatory checklist. Moreover, defining the fundamental objects and relations involved in water quality monitoring is necessary for establishing representative data structures, which are absolutely critical for managing the future deluge of useful operational data waiting in the pipeline (apologies) as regional and national water quality programs grow worldwide and environmental sensors become more connected (Babitski et al. 2009, Fonseca et al. 2002, Russomanno & Tritenko 2010, Eastman et al. 2013). For this reason, the ontological relationships of water quality monitoring are also described (somewhat less comprehensively than by Kuhn [2007]) in the language of the Open Geospatial Consortium's (OGC) Observations and Measurements specification (OGC 2014; hereafter "OM specification"), which has informed the draft OGC WaterML-WQ information model for water quality data (Simons & Cox 2014). Adopting ontological considerations into water quality monitoring standards would presumably better enable coordination between the normative and analytic arms of regulatory activity.

Still, there are broader issues yet to be considered, and it may be worth continuing our exploration with a more concise approach.

2.9 A proposal for an international, base-tier water quality monitoring device assessment program

Having begun an exploration of nephelometry from the framework of a formal ontology, let us abstract to the level of a simple conceptual model to capture the broader context of water quality monitoring activities for the protection of human health (in a less exhausting manner of description). Figure 2.2 adumbrates this "USED MILQ" conceptual model (name formed from letters in the figure) with the parsimony of a cave painting.

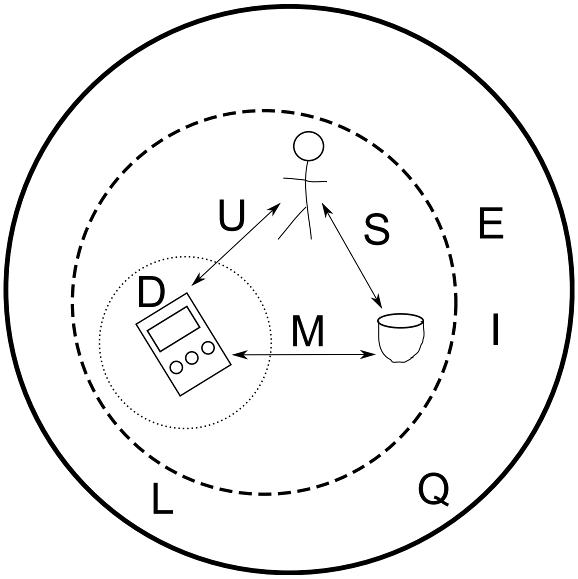

Figure 2.2. The “USED MILQ” conceptual model of water quality monitoring device development.

The stick figure person in the diagram represents the users of the monitoring device in this conceptual example. They interact with an aqueous sample (represented by the small cup) and a monitoring device (the small rectangular icon with buttons and a screen) to take measurements of analytes of interest. There are three circles in Figure 2.2, each of which bounds a conceptual distance. From smallest to largest, these are the locus of the device per se (dotted border), the locus of measurement (dashed border), and the extent of the all aspects of the external environment relevant to the monitoring device and to the act of monitoring (solid border).

The letters in Figure 2.2, which are placed within the most relevant boundary, represent the following key aspects of the proposed conceptual model:

U – User interface requirements, to ensure that people of varying ages and education levels can usefully interact with monitoring devices.

S – Sampling requirements, to ensure that aliquots are representative of the water from which they are obtained with respect to the analyte of interest. Note that while these requirements are of paramount importance for proper monitoring, they are beyond the purview of instrument design. Users should refer to relevant national monitoring laws or WHO recommendations for guidance.

E – Environmental interface requirements. Note that “Environment” here refers to several areas of interest external to the locus of monitoring (as discussed in Section 2.8).

D – Device requirements, which include consumer-centric concerns such as environmental access to markets for affordable monitoring devices, and producer-centric concerns such as regulatory guidance for producing acceptable and useful monitoring devices.

M – Measurement requirements, which are logically split into two sections: general statistical and engineering requirements for taking reliable measurements with a particular monitoring device, and analyte-specific measurement requirements.

I – Interactive requirements, specifically requirements for communication of the act of measurement with the broader community (e.g. data analysis and communication to stakeholders).

L – Legal issues including monitoring frameworks, legal requirements for regular monitoring of drinking water supplies by licensed water providers as well as permissibility of environmental monitoring by private citizens and non-governmental organizations.

Q – Quality assurance and quality control (QA/QC), including verification of the performance claims of monitoring device manufacturers, of the long-term reliability of individual monitoring devices, of the veracity of data captured by human observers through the purported use of monitoring devices, of the integrity of data transmission chains, of the ability to draw conclusions from sets of environmental monitoring data.

Regulatory awareness of end-user needs and means

Many philosophers have noted the difficulties inherent in assuming that science is or could be value-neutral, a position forcefully argued by Habermas in the context of state-funded scientific research in capitalist societies (e.g. Habermas 1968). As Harding (1991) and Habermas (1968) have noted, neither scientists individually nor science as a collective endeavor can lay claim to being value-neutral, and the assertion of value-neutrality in science often amounts to a fig leaf over the dominant sociopolitical paradigm in which that science is rooted. Longino (1996) discusses the need to address the applicability of scientific inquiry to human needs when considering epistemic frameworks. Addressing such frameworks for geographical systems, Couclelis (2009) argues that it is crucial to identify the stated and unstated purposes of the geographical ontologies we construct, because these purposes serve as the bridge “between the world of geospatial entities on the one hand, and the social world of intentional agents on the other.” She continues:

“Purpose determines what spatial functions need to be represented, what distinct spatial entities belong together to form a complex object, how simple objects are named and categorized, what spatial patterns and measurable properties correspond to the entities of interest and how these should be analyzed, what sort of information is relevant, and finally, what spatio-temporal framework must underlie the representations appropriate for the purpose in question."

Proper, consistent use of water quality monitoring devices has global and daily purposes of investigating our environment and safeguarding human health. The choice of sampling protocol employed in a given area is a globally decentralized issue; a political and policy matter for each nation or community to decide. The development and manufacture of the devices that ultimately will effect those measurements, on the other hand, is at present a highly centralized endeavor. The current situation of water quality monitoring device design and manufacture seems to be rooted in the rational, self-interested actions of economically and politically dominant nations to promulgate specific, repeatable, abstracted laboratory methods, which form the basis for the engineering efforts by which the commercial markets for water quality monitoring devices are filled.

If in the design of a monitoring device we do not consider the intended purpose and outcomes of a monitoring activity, we may simply design for "default" purpose to fit whatever dominant paradigm is considered the default case. I would argue that this is precisely what has happened in the commercial market for water quality monitoring hardware over the past few decades.

2.10 Summary

What follows from here in Chapter 3 is a first attempt at a program which, in recognition of the concerns identified in current EPA and ISO turbidity regulations, describes turbidimeter development regulations that are intended to facilitate distributed efforts to produce WHO-compliant turbidimeters for global water quality monitoring. The "USED MILQ" conceptual representation of water quality monitoring is coupled with a normative description of how to meet the measurement need described in a local, regional, or global context, through appropriate device development guidance. In line with the general taxonomy of an open-source hardware development effort, outlined above, this guidance emphasizes iterative development with feedback. Impacts of design choices on ability to meet the CAMO principle are evaluated at each design stage. The draft regulations and guidance documentation outlined in the next chapter are intended to serve as a broad template of device design for water quality monitoring. Mindful of the scope of work required of that endeavor, however, the present effort chiefly addresses only turbidity.

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Chapter 3: The AWQUA Framework: proposed guidance for the development of open-source water quality monitoring devices

3.1 Chapter foreword

As described in Chapter 2, various distinctions exist between accepted minimum international guidelines for drinking water quality promulgated by the WHO (WHO 2017) and the very influential drinking water quality standards promulgated by the EPA (EPA 1993) and the ISO (ISO 2016). Moreover, water quality monitoring technology for the commercially important US and European regulatory markets must be designed to EPA and ISO specifications which are based on their respective drinking water quality standards. There are no official standards to guide the development of commercial drinking water quality monitoring technology pursuant to WHO water quality guidelines – that is, technology that we might call "WHO-compliant". Given the geographic distance and the relatively low purchasing power (relative to the USA and EU) of the vast majority of communities around the world where commercial EPA- and ISO-compliant water quality monitoring devices are unaffordable or unmaintainable, open-source hardware and software development efforts are broadly examined in the previous chapter as a possible mechanism for encouraging the development of WHO-compliant water quality monitoring devices. It is noted that (1) specific standards for the performance of WHO-compliant water quality monitoring devices must be articulated; (2) that such standards might be logically adapted from existing EPA and ISO monitoring technology certification standards; and (3) that efforts to develop WHO-compliant open-source water quality monitoring equipment may need considerably more development guidance and regulatory scrutiny than parallel commercial development efforts have required. As a first step towards addressing these concerns, a standard framework is proposed for the development of open-source water quality monitoring devices. The proposed framework comprises analyte-specific performance standards for designing WHO-compliant monitoring devices and a general framework for the development of WHO-compliant open-source water quality monitoring devices. A key design feature of the general framework is that the process of developing a water quality monitoring device in line with this framework should result in the production of device performance documentation suitable to certify that the analyte-specific performance standard is met. An articulation of this two-part framework, dubbed the Affordable Water Quality Analysis (AWQUA) Framework, is the subject of this chapter.

An open-source turbidimeter that partly motivated the development of the AWQUA Framework is detailed in Chapter 4. Chapters 5-7 detail open-source drinking water quality monitoring devices that were largely developed alongside, and in some respects before, this framework was developed. The documentation procedures, and some design elements, of the proposed and prototype devices have been reworked to address the requirements of this framework. They are intended to serve as examples of how the guidance framework can be utilized for developing WHO-compliant monitoring devices, and hopefully can help spur both improvements to this framework and the development of more affordable and more capable water quality monitoring devices.

3.2 The AWQUA Device Development Framework: stages and requirements

The AWQUA Framework is intended to provide guidance for open-source water quality monitoring device development, and to serve as a documentation checklist to permit self-certification of open-source and closed-source water quality monitoring devices that have been developed to meet an AWQUA water quality monitoring standard. While the AWQUA Framework is intended to be a general guidance framework, the language may not meet needs for evaluating monitoring of all water quality monitoring parameters. It is hoped that subsequent efforts can evolve and improve this framework over time.

This framework recognizes four descriptive stages of device development – Proposed Design, Prototyped Design, Provisional Design, and Registered Design. The requirements for each stage are outlined below.

1. Proposed Design.

Summary

The "Proposed" stage of the AWQUA Framework is designed to provide a public starting point for collaborative device development. A thorough description of a proposed device (the parameter to be measured, measurement mechanism, power supply, size and shape of the device (hereafter referred to as "form factor"), data transmission chain, mechanism that triggers the measurement process (hereafter referred to as "actuation mode"), and the context of its proposed use (existing equivalent measurement devices, existing regulations governing the design of such devices, and existing met and unmet global need for a device such as that proposed) are required.

The Proposed stage is intended to encourage methodical explanation and contextualization of a design problem before the prototyping of a design solution is undertaken. The collective knowledge gathered in this design stage is structured to be generalizable for a given water quality monitoring niche. Further, by providing a preliminary stage that requires documentation on a diverse set of factors related to a monitoring activity, the Proposed stage aims to encourage collaboration between people who have a detailed understanding of the need for a particular monitoring device but little idea of how to construct one, and people who have a detailed understanding of microelectronics but little conception of the urgent global need for affordable water-quality monitoring devices.

Requirements

Each Proposed device must have a parameter-specific guidance document, which (as for all AWQUA development stages) is to be organized in accordance with the "USED MILQ" conceptual model described in Chapter 2; items within each category are numbered sequentially across stages.

Responses to these sections need not be exhaustive but should be detailed enough to help other people understand and contribute to the proposed design.

To designate a monitoring device as a Proposed Design within the AWQUA Framework, the following is required:

NB: Requirements followed by an asterisk (*) are required by any AWQUA-compliant device, even if it enters the documentation process at a more advanced development stage.

User:

(U1) A description of the population of end users envisioned (e.g. “rural communities in developing countries”).

Sampling:

(S1) A summary of any known sampling issues which may affect the measurement process or the operation of the Proposed device (e.g. “when conducting turbidity measurements cuvettes must be wiped and dried, both to remove any dirt from the outside of the cuvette and to dry the cuvette and prevent damage to the device electronics”).

Environment:

(E1) A description of the intended geographical areas where device use is envisioned (e.g. “surface water monitoring in tropical areas”).

(E2) Existing literature on the applications of the proposed mechanism for measuring the intended parameter;

(E3) A listing of relevant, currently available commercial monitoring devices;

(E4)* An explanation as to why the proposed device should be developed and employed (e.g., rather than an equivalent existing device being employed).

Device:

(D1) A statement of the intended form factor, power source, use setting, data transmission chain, and actuation mode of the proposed device;

(D2) A detailed sketch of the proposed monitoring device should be included in the documentation to provide visual reference to each of the items identified in (D1).

Measurement:

(M1) A description of the parameter to be measured, and an explanation of the relevance of this parameter to water quality testing;

(M2) A description of the measurement mechanism to be used, as well as other common measurement mechanisms that have been or can be used for the parameter indicated, including a brief comparison of the advantages and disadvantages of the proposed measurement mechanism relative to the other mechanisms listed.

Interactive:

(I1)* Descriptions of devices at all stages of the AWQUA development framework must be posted in a publicly available online repository (e.g. GitHub).

Legal:

(L1) Documentation of primary measurement standards and testing procedures (e.g. EPA, ISO, WHO), if any, for the proposed pair of analyte and measurement mechanism;

(L2) A statement acknowledging and crediting all members of the device development team for their contributions.

Quality assurance / quality control:

No information required.

Construction, Affordability, Maintenance, Operation (CAMO) summary:

All devices in the AWQUA Framework should be able to meet the CAMO principle. Each phase of the AWQUA Framework includes a CAMO document summarizing how design choices affect these bottom lines. For the Proposed Design phase, the CAMO summary should outline the areas of the world and measurement niche for which the device is intended, and list any major concerns or hurdles to be overcome in subsequent design stages.

2. Prototype design.

Summary

Once the Proposed device has been documented, specific device designs should be considered and documented in the Prototype Design stage. While the development of commercial hardware and software is typically conducted by closed research and design teams, to maintain the knowledge asymmetry and business advantage that justify commercial development efforts, open-source design efforts are frequently conducted through a public development process that may involve a few or possibly thousands of developers sharing knowledge and work across various public platforms. The ability of open-source development efforts to recruit decentralized and arbitrarily large volunteer teams is potentially a very powerful instrument, but with larger teams and the involvement of non-expert volunteers comes the need for greater structural management of the device development process.

The AWQUA Framework distinguishes three phases of prototyping, thus providing a structure to develop the adumbrated device design notes of the Proposed Design stage into a deployable, testable monitoring device. Each of these three phases (detailed below) entails additional documentation and testing requirements.

Phase I requires a research team to map the identified measurement niche to a particular device design, to demonstrate the logical merit of that device design, and to provide basic data on the ability of the described measurement mechanism. Phase II requires a research team to provide a specific and replicable implementation of the described measurement mechanism, to establish measurement utility by providing calibration, validation, and drift datasets, and to match the demonstrated measurement capabilities to an established water quality standard. Phase III requires refinement of the measurement mechanism, encasement of the measuring device in an exterior suitable for its intended use environment, the provision of a user interface suitable for technical users, a conservative estimate of the re-calibration frequency required, description of the re-calibration procedure, and calibration, validation, and drift datasets after an initial calibration and a re-calibration.

To establish a Prototype design, the following documentation is required:

Requirements

NB: Requirements followed by an asterisk (*) are required by any AWQUA-compliant device, even if it enters the documentation process at a more advanced development stage.

Phase I

User:

(U2) Any new or revised information about the envisioned end-user population description from (U1).

Sampling:

(S2) Any new or revised sampling issues encountered since (S1).

Environment:

(E5) Any new or revised information for (E1) on the intended geographical areas where device use is envisioned.

Device:

(D3)* Circuit description, consisting of a schematic, and either a Printed Circuit Board (PCB) layout (in, e.g., EagleCAD format [Autodesk 2018]) or breadboard layout (in, e.g., Fritzing [Fritzing 2018]);

(D4)* A Logic of Operations description, detailing how the device will interface with a user, and take, calculate, store, display, and transmit measurements;

(D5)* A diagram of the structural components of the measurement mechanism (e.g. a cuvette chamber or optical window);

(D6) A Bill of Materials (BOM), detailing the electrical components of the measurement mechanism;

(D7)* Datasheets for key electrical and structural components.

Measurement:

No information required.

Interactive:

No information required.

Legal:

No information required.

Quality assurance / quality control:

(Q1) Proof of operational measurement utility must be provided in the form of a basic measurement data set, along with a summary of how the device was operated to obtain the data.

Phase II

User:

(U3) A conservative estimate of how frequently calibrations should be performed, based on available information on the measurement mechanism and the testing data for the specific device.

Sampling:

No information required.

Environment:

(E6) A “Cost at Scale” (CAS) BOM with suggested suppliers and hardware costs for manufacturing runs of 1 to 1,000 units in decades.

Device:

(D8) Circuit design files (e.g. EagleCAD BRD/SCH files, as well as CAM files in Gerber RS274-X [GSC 2001] format)

(D9) Firmware code in a common language (e.g. Arduino [Arduino 2017], C [Kernighan & Ritchie 2006], MicroPython [MicroPython 2018], MBED [ARM 2018], FreeRTOS [RTE 2017]);

(D10) Software code, if any;

(D11) A description of the data storage schema used, if any;

(D12) A description and link to any firmware or software libraries used to build the device’s code;

(D13) Design files of internal structural elements, if any, in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD);

(D14) Design files of internal structural elements, if any, in a common interchange format (e.g. STL, DXF).

Measurement:

(M3) A description of the device calibration procedure and re-calibration procedure (if different);

(M4) A description of the procedure by which calibrations will be verified and the measurement precision and accuracy of the device ascertained. This should include consideration for how to measure drift over time and temperature ranges (and appropriate ranges for any other confounder variable identified in [L3] below).

Interactive:

(I2) Following completion of all other requirements in Phase II, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

Legal:

(L3)* The specific water quality monitoring standard or guideline for which the Prototype device is intended to be a suitable measurement device.

Quality assurance / quality control:

(Q2) Calibration data, from a calibration procedure conducted according to the water quality monitoring standard selected in (L3).

(Q3) Validation data, from a validation procedure conducted according to the water quality monitoring standard selected in (L3).

(Q4) Drift data, showing the consistency of readings taken with the same Prototype device over time, and across the range of ambient conditions for measurement confounder variables identified in (M4) (or as required by the analyte-specific standard and appropriate for the intended environment of use).

Phase III

User:

(U4)* Ease-of-use reports from a tester from a selected and identified range of prototype testers;

(U5) Hardware assembly instructions;

(U6) Device programming instructions;

(U7) Caseware manufacturing and assembly instructions;

(U8)* Operating instructions, including how to take validation, drift, and recalibration measurements;

(U9)* Reports of operational issues from at least two weeks of regular use, in conditions that match the use environment identified in (E5) as closely as is feasible.

Sampling:

(S3)* If the standards specified in (L3) contain sampling requirements, these must be clearly stated in device documentation and followed whenever a requirement at or beyond this stage requires sampling.

Environment:

(E7) “Bill of Fabrication” (BOF), which outlines the costs of all equipment and services used to produce the Prototype;

(E8) An estimate of the time, and labor, required to produce a Prototype.

Device:

(D15) Case design files in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD);

(D16) Case design files in a common interchange format (e.g. STL, DXF);

(D17) Durability summary, including a summary of likely failure points of external and internal structural elements;

(D18) A summary of challenges and opportunities in the current Prototype design.

Measurement:

(M5) If the standards specified in (L3) contain measurement requirements, these must be clearly stated in device documentation and followed whenever a requirement at or beyond this stage requires measurement.

Interactive:

(I3) Following completion of all other requirements of Phase III, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

(I4) A certification of successful data flow.

Legal:

No information required.

Quality assurance / quality control:

(Q5) Calibration, validation, and drift datasets;

(Q6) Recalibration data, showing the agreement of a calibrated device before and after recalibration;

(Q7) A power drain analysis and estimate of use per charge cycle or battery change (if applicable).

CAMO Summary:

Construction

Address any difficulties in manufacturing due to parts selection. Integrated Circuit (IC) form factors that require x-ray inspection for proper quality control should be strictly avoided unless designing for countries with robust electronics assembly industries with proven capacity to perform these assembly and QA/QC tasks. Additionally, whenever possible, avoid IC's with pitch smaller than 0.8mm and passive components with form factors smaller than 0603 to aid manual placement (see Brindley 1999 for further discussion). Additionally, jumper wires between circuit boards should be replaced at Phase III with proper cable assemblies, or better still with combination and integration of circuit boards – unless the device is designed chiefly for educational purposes. Note any use of such components as an outstanding issue for small-scale manufacturing and a target for future design improvement.

Affordability

Note any improvements to CAS estimates, and include shipping and import/customs duties estimates for the identified component supplier(s).

Maintenance

Detail all materials necessary for recalibration and other routine maintenance activities, and specify where they may be obtained.

Operation

Using the "USED MILQ" conceptual model of the monitoring environment, identify any likely impediments in employing the Prototype monitoring device.

3. Provisional design.

Summary

The Provisional stage is intended to transition promising devices from in-house development in prototype quantities to replicated, small-scale manufacturing. It is also the first stage for an open-source fork of a closed-source monitoring device (with additional documentation requirements from Proposed and Prototype stages noted with asterisks).

Requirements

To receive provisional approval for a prototype design, the additional following documentation is required.

NB: Requirements followed by an asterisk (*) are required by any AWQUA-compliant device, even if it enters the documentation process at a more advanced development stage.

User:

(U10) Any new or revised information about the envisioned end-user population description from (U2).

(U11) A product introduction video, in English (at minimum), must be produced to familiarize potential customers with the device. This introduction video must be made publicly available online, in a common free video hosting platform such as YouTube (Google 2018).

Sampling:

(S4) Any new or revised sampling issues encountered since (S2).

Environment:

(E10) Any new or revised information for (E5) on the intended geographical areas where device use is envisioned.

(E11) Setup cost for manufacturing facility, and per-unit cost at scale (1 – 1,000 units in decades), fully detailed.

Device:

(D19) Any design changes made during the Provisional phase, and update the respective documents (schematic & board, BOM & CAS, BOF, caseware files). If changes were made to power train rerun (K7); if changes made to data communication hardware rerun (I4).

Measurement:

See (M2).

Interactive:

(I5)* Documented agreement with two suitable external agents to conduct use tests, including device operation, recalibration, and revalidation;

(I6)* Documented agreement with one suitable external agent to construct, calibrate, and validate the prototype device;

(I7)* Ten fully constructed prototype units, at least five of the ten constructed by the external manufacturing agent;

(I8) Following completion of all other Provisional Stage requirements, documentation of the Provisional Design must be finalized and left unedited for at least two weeks. The device and its documentation must be promoted to interested parties (e.g. Appropedia, Public Lab, Akvo). Any comments received during this period must be addressed before proceeding to the Registered phase.

Legal:

(L4)* All device design files must meet AWQUA documentation guidelines.

(L5)* If the device is open-source, it must have appropriate license(s) (e.g. GNU-GPL [FSF 2007] or MIT [OSI 2006] for software, Creative Commons [CC 2017] for circuit board layout and caseware). Additionally, device documentation must be reviewed for any gaps or errors that would prevent Open Source Hardware Association (OSHWA) self-certification (see http://certificate.oshwa.org/).

Quality assurance / quality control:

(Q8)* Operation, recalibration, and revalidation data from independent testers;

(Q9)* Construction, calibration, and validation data from independent manufacturer;

(Q10)* Long-term use – bug reports and usage reports from at least two weeks of daily use of ten prototype units, which must take place in the intended environment of use identified in (E5);

(Q11) Standard-specific review of data (showing how the data collected meet the requirements of the stated primary or secondary monitoring standard).

CAMO Summary:

Construction

No information required.

Affording

Provide a five-year cost comparison of the Prototype device and an equivalent commercial monitoring device, including purchase, operation, maintenance, and depreciation.

Maintenance

Outline the manufacturing setups of the two (or more) manufacturing teams, and provide any manufacturing failure reports.

Operation

No information required.

4. Registered design.

Summary

The Registered stage marks the end of the documentation process for a given device design. A large pool of devices (50+) must be tested for an extended period (6+ weeks) in realistic settings. Bugs must be logged and addressed, and user instructions translated into target languages.

Requirements

To receive full AWQUA registration for a design, the additional following documentation is required.

NB: Requirements followed by an asterisk (*) are required by any AWQUA-compliant device, even if it enters the documentation process at a more advanced development stage.

User:

(U12) Any new or revised information about the envisioned end-user population description from (U11).

(U13) An updated version of (U11), in English (at minimum), must be produced to familiarize potential customers with the device. This introduction video must be made publicly available online, in a common free video hosting platform such as YouTube (Google 2018).

(U14) Written device operation instructions, in English (at minimum). It is preferred that instructions are also made available in other languages that target previously identified target user groups (if any). These instructions must be made publicly available online.

(U15) Audiovisual device operation instructions, in English (at minimum), in the form of a video user guide. All points in the written instructions, (U14), must be covered in the video user guide. It is preferred that instructions are also made available in other languages that target previously identified target user groups (if any). These instructions must be made publicly available online, in a common free video hosting platform such as YouTube (Google 2018).

Sampling:

(S5) Any new or revised sampling issues encountered since (S4).

Environment:

(E11) Any new or revised information for (E7) on the intended geographical areas where device use is envisioned.

(E12) Complete costs detailed by independent manufacturer.

Device:

(D20) Any design changes made during the Registered phase, and update the respective documents (schematic & board, BOM & CAS, BOF, caseware files). If changes were made to power train rerun (K7); if changes made to data communication hardware rerun (I4).

Measurement:

See (M2).

Interactive:

(I9) Fifty devices constructed by two or more independent manufacturers;

(I10) Testing partnerships established with two or more independent testers;

(I11) All documentation integrated into online repository;

Legal:

(L6) If open-source, device must meet self-certification criteria as defined by OSHWA, and must be certified and labeled with the OSHWA logo.

Quality assurance / quality control:

(Q12) Operation, recalibration, and revalidation data from independent testers;

(Q13) Construction, calibration, and validation data from independent manufacturer;

(Q14) Long-term use reports from at least six weeks of twice-weekly use of 50 prototype units;

(Q15) Bug reporting integrated into online repository for design.

CAMO Summary: Any issues that arise during the Registered stage that pertain to the CAMO principles should be flagged for future design improvement, with notification in public repositories to solicit public comment.

3.3 Analyte-specific AWQUA draft standard: basic turbidity monitoring

3.3.1 Foreword

This proposed AWQUA standard was drafted to provide an alternative to the device design requirements in the current international (ISO 7027) and American (EPA Method 180.1) nephelometry standards. Below, I describe several new specifications that are absent or unclear in the EPA and ISO methods, to provide clarity and guidance for smaller commercial and open-source device development efforts. Additionally, unlike the EPA and ISO methods the proposed AWQUA nephelometry standard is intended to guide the construction of WHO-compliant turbidimeters (which entails accurate detection at 1.0 NTU or lower).

3.3.2 Nephelometer development standards

Temperature: Changes in temperature can dramatically affect the accuracy of a turbidimeter system that does not contain effective compensation techniques. Many components of turbidimeters, including LEDs, operational amplifiers, analog-to-digital converters, and even simple components like resistors, can have operationally relevant temperature coefficients. EPA and ISO standards specify temperature requirements for the preparation of the turbidity standard formazin; however, they do not acknowledge the interfering effects that temperature can have on the operation of an electronic turbidimeter nor stipulate testing or performance requirements to address fluctuations in ambient temperature during turbidimeter operation.

The AWQUA basic turbidity standard stipulates the following generic operational temperature range for turbidimeters:

1. Full operational temperature range: 5C to 45C

It is worth noting that for specific markets and uses (such as field monitoring with handheld turbidimeters in tropical regions, or immersive inline monitoring) a smaller temperature range may be sufficient to capture typical operating conditions. Since a smaller stipulated operational temperature range may allow for device cost reductions, the AWQUA basic turbidity standard additionally recognizes two draft temperature range subsets:

2. Handheld monitoring in tropical regions: 15C – 35C
3. Inline monitoring in tropical or temperate regions: 10C – 27C

A device compliant with this standard must specify one of the above operational temperature ranges, and must have accompanying test data demonstrating that the measured turbidity of a 100 NTU sample does not vary by more than 2% across the operating temperature range. One data point must be captured at each end of the stated operating temperature range, and at 10C intervals within that range.

Light: This standard stipulates an LED-based turbidimeter which must meet ISO 7027 requirements for beam angle (0 +/- 1.5 degrees), alignment (90 +/- 2.5 degrees from detector for nephelometry; 0 +/- 2.5 degrees from detector for attenuation), wavelength (860 nm), spectral bandwidth (60 nm), and aperture (10 to 20 degrees). Additionally, this standard stipulates a maximum path length of 10cm (as in EPA Method 180.1) and further stipulates that a compliant turbidimeter shall not have a path length below 1.5 cm unless design requirements – which must be explained in the device documentation – require it.

It is noted that the beam angle requirement of the ISO regulations is potentially onerous for device developers because such a narrow beam would typically require a high-cost LED, a hybrid laser device such as a vertical-cavity surface-emitting laser (VCSEL). Additionally, a wide-angle LED incorporated into a dual-detector setup for dynamic temperature compensation presents a potential reason to depart slightly from ISO 7027 light requirements. Therefore, the AWQUA basic turbidity standard shall permit an LED with any beam angle so long as a beam guide, such as a lens or an optical fiber, is placed between the LED and the cuvette chamber and stray light from the LED is blocked. Additionally, if the turbidimeter being developed is an inline device utilizing backscatter detection, an angle between 30 and 150 +/- 2.5 degrees is permitted.

Casing: Casing is unaddressed in EPA and ISO standards. Optical components must be housed in a solid metal or polymer substance, and optical distortion caused by reasonable manual deformation of an encased turbidimeter must affect a standard test batch of turbidity readings by no more than the greater of 0.1 NTU or 0.5%.

Cuvettes: Removable cuvettes used for handheld turbidity monitoring must be (1) made of clear glass or plastic, (2) aligned in the cuvette holder to minimize optical distortions caused by surface irregularities, and (3) discarded when they become scratched or damaged, as stipulated by EPA and ISO regulations.

Detection: The AWQUA basic turbidity standard is targeted to the development of a turbidimeter that can meet WHO turbidity monitoring standards. As such, the ideal turbidimeter under this standard would be able to reliably monitor turbidities as low as 1 NTU without any error. Given that error-free operation is an unrealistic expectation, EPA and ISO standards define statistical requirements for turbidimeter behavior. The following terms and requirements apply for the AWQUA basic turbidity standard:

(i) Trueness: ISO 7027 relies on measurement definitions given in ISO 5725 (Accuracy (trueness and precision) of measurement methods and results (ISO 1994), which defines trueness as equivalent to "the bias of a large number of measurements". The EC Directive on Drinking Water (OJEU 1998) sets a trueness target for turbidity measurements at 25%. As this is larger than the 10% maximum bias allowed by the EPA's Instrument Performance Check protocol, and since the "large number" of measurements required to assess trueness is unquantified in the above-mentioned documents, the AWQUA basic turbidity standard stipulates that a compliant turbidimeter must be able to demonstrate a trueness of 10% or better at 1.0 NTU for a standard test batch.

(ii) Precision: The EC Directive on Drinking Water, in accordance with ISO 7027 and ISO 5725, states that acceptable precision ("random error within and between batch") is equal to twice the standard deviation of a large number of samples. The Directive further states that a precision of 25% is permissible for turbidity measurements at a parametric target value of 1.0 NTU. This would imply (assuming normality) that roughly 95% of measurements of a 1.0 NTU sample would fall between 0.75 NTU and 1.25 NTU, but does not address acceptable standard deviations for other values. Since the EPA and ISO turbidity regulations do not specify acceptable standard deviation intervals, the AWQUA basic turbidity standard simply stipulates that standard deviation of a batch of readings must be reported to the user (see Reporting requirements section below).

(iii) Limit of detection: The AWQUA basic turbidity standard follows the definition of Limit of Detection (LOD) specified by the EC Directive on Drinking Water (98/83/EC), the limit of detection (LOD), stipulates that for a given turbidimeter the LOD shall be given as “five times the within-batch standard deviation of a blank sample”, where a batch will be a standard test batch and a blank sample will contain water with turbidity of 0.02 NTU.

(iv) Range of detection: The AWQUA basic turbidity standard recognizes two use cases that require differing ranges of detection:

(1) monitoring of drinking water (or monitoring for compliance with drinking water regulations)
(2) monitoring of raw water (or monitoring that is not for compliance with drinking water regulations)

Lower end of range: EPA turbidity regulations require that a turbidimeter be able to detect a difference of 0.02 NTU over the range of 0-1 NTU, however the required trueness and precision of this detection event are not stipulated. For drinking water monitoring, the minimum detection target of this AWQUA standard is the WHO recommended maximum turbidity level for treated drinking water (1.0 NTU). It will be considered sufficient for a device compliant with this standard be able to measure down to 0.8 NTU (the minimum detection standard minus twice the maximum

> deviation allowed by the EPA’s IPC criteria) or lower with a trueness of 10% (following EPA IPC) and a precision of 25% (following the EC drinking water directive). For raw water monitoring that is not for drinking water regulatory compliance, the capability to measure down to 5 NTU at 10% trueness and 25% precision will be considered acceptable (to reduce device development costs).
>
> Upper end of range: A device compliant with this AWQUA standard must specify its upper end of detection range, and must always warn the user when the mean of a batch of readings is outside the device’s measurement range. For drinking water compliance monitoring a device must be able to measure at least 40 NTU for drinking water monitoring (corresponding to the upper end of the linear range of nephelometric detection), and no more than 1000 NTU unless a second light detector in a ratiometric setup is utilized (in which case the upper range limit is 2000 NTU). For raw water non-compliance monitoring, the upper range should not exceed 2000 NTU for a ratiometric or backscatter setup (or 1000 NTU for a basic nephelometric setup).

Reporting: The EPA and ISO standards discuss measurement requirements in detail, but do not require that details of turbidity measurements beyond the sample mean be reported to the end user. The AWQUA basic turbidity standard stipulates that a compliant device must be capable of calculating and displaying these data to the user following a read event:

1. Number of replicate readings conducted during read event
2. Unadjusted sample mean and standard deviation of replicates
3. Whether ambient light was subtracted from readings, and if so whether this was via software calculations or via hardware
4. A basic histogram, with at least six equal-interval breaks, of unadjusted replicate readings

5. A warning if more than 10% of replicate readings are beyond two standard deviations from the unadjusted sample mean and the unadjusted sample mean is above 1.0 NTU.
6. Whether the sample mean and standard deviation were adjusted by removing outliers beyond two standard deviations from the replicate readings
7. If (6), the adjusted sample mean and standard deviation of replicates
8. If (6), a basic histogram, with at least six equal-interval breaks, of adjusted dataset
9. The operating voltage level of the device
10. The ambient internal temperature of the device
11. The nominal brightness level of the LED, if adjustable and/or if measured by a separate, dedicated detector
12. The diode junction temperature of the LED, if measured
13. The sample mean and standard deviation of the dark count, using a minimum of ten replicates
14. The timestamp of the beginning of the read event
15. The geographical coordinates of the read event, if available

Data must be displayed visually, and also by other means if accommodating the visually impaired; this may be accomplished directly via an on-device monitor, or indirectly via a connected display device (such as a cellphone tethered by Bluetooth). To be able to accommodate users of different training levels, it is permissible for a compliant turbidimeter to have subsets of data displayed for basic use, advanced use, and programming. For basic use, only items (2) (or (7) if (6) is true), (5), (9), (10), and (14) must be displayed or recorded. For advanced use, items (2), (5), (6), (7), (9), (10), (12), (14), and (15) must be displayed. All items must be displayable or transmittable (the latter via a common communication protocol such as Bluetooth, JTAG, or RS-232 Serial) for programming use.

Power: A device compliant with the AWQUA basic turbidity standard must contain an internal battery (which can be disposable or rechargeable), or accept connection to an external DC power source, and must be able to conduct 100 separate read events (each a standard test batch) before this battery (or external power source) requires recharging or replacing. Variation in system power due to voltage spikes or battery drain shall not be allowed to affect turbidity readings by more than the greater of 0.05 NTU or 0.1%.

Data persistence: For all data elements described in the Reporting section, a device compliant with this standard must be able to provide real-time data telemetry of readings, or removable on-board storage (with time-stamping) for at least 100 readings.

3.3.3 Calibration and recalibration

Calibration of a turbidimeter is the establishment of an interpolation curve, which covers the device's range of measurement between the native units of a turbidimeter (such as millivolts or Hertz) and standard turbidity units such as NTU. For the purposes of this standard, calibration refers to both initial factory calibration by the manufacturer and calibration conducted by a qualified repair center (once such qualifications are detailed and certification procedures described). Recalibration refers to a calibration carried out by the end user (assuming they are not the manufacturer nor a qualified repair technician).

In EPA and ISO regulations, calibration is conducted using freshly prepared turbidity primary standards: suspensions of the polymer formazin in deionized water with known turbidity levels. However, formazin suspensions can be difficult and dangerous to prepare. The preparation requires a 10:1 mixture of hexamethylenetetramine and the highly toxic chemical hydrazine sulfate in a reaction that must be kept at 25C (+/-3C) during a typical 24-hour reaction period, which entails a significant measure of active ambient temperature regulation (EPA 1993). Formazin suspensions are only shelf-stable in high concentrations and at a constant room temperature, and the high level of dilution required to make low-turbidity standards for calibration kits requires ultra-pure water and precise instrumentation (Buzoianu 2000). While both EPA and ISO standards allow the use of pre-calibrated shelf-stable secondary standards for day-to-day calibration checks of turbidimeters, these commercially available standards are expensive and – like commercial turbidimeters – are typically manufactured far away from LRS communities. These aspects of primary turbidity standards preparation present potential problems for turbidimeter manufacturing and calibration in LRS. While some use of formazin as a primary turbidity calibration standard may be inevitable even in developing countries – say, in a nationally accredited lab in a major city – it seems undesirable and unwise to promulgate nephelometry guidelines that would so strongly rely on the use of primary calibration standards, or commercial secondary standards, as to make local production of those standards in LRS a practical necessity.

It is acceptable under the AWQUA basic turbidity standard to conduct a turbidimeter calibration according to EPA or ISO stipulations. Given the difficulties inherent in the production and storage of formazin, the AWQUA basic turbidity standard also recognizes two alternative calibration procedures:

(1) (*Preferred*) Calibrating against fresh secondary calibration standards such as ProCal or StablCal. These are pre-mixed suspensions of a formazin-like polymer which, while somewhat expensive and still temperature-sensitive, are non-toxic and ready-to-use.

(2) (*Acceptable*) Calibrating against a set of well-mixed colloidal suspensions – such as hydrophilic cutting oil in distilled water – the turbidity value of which has been freshly evaluated by a well-calibrated commercial turbidimeter. It should be noted that this method, as it relies upon turbidity values determined by a separate turbidimeter, rather than by stoichiometric precision (in the case of primary and secondary standards preparation), is more correctly termed assessment of agreement than calibration (Bland & Altman 1986).

Each such measurement must be a standard test batch. The calibration range must extend beyond the intended detection range of the turbidimeter (i.e. it must yield an interpolation curve, not an extrapolation curve), and must contain at least five calibration points (as required by the ISO standards) if a single linear regression is used to characterize the calibration curve. For a series of linear calibration ranges, the calibrator must use at least three points per calibration range. In contrast to the EPA standards, the sections of the calibration curve in between these calibration points do not need to be linear; they may be polynomial so long as a polynomial regression is used to characterize them. For quadratic and cubic calibrations, a minimum of four and five points are needed per range, respectively. Polynomial regressions with a degree higher than three are not permitted.

Whichever of the three calibration options is used, all details of the calibration procedure must be documented in electronic form and shared with the end user. Additionally, instructions for a recommended recalibration procedure, and recalibration timeframe determined during the AWQUA certification process, must be shared with any purchaser or end user.

NOTE: The use of temperature-sensitive liquid turbidity standards – whether primary or secondary – is logically a bottleneck in the global use of accurate turbidity monitoring for public health and wellbeing. Polymer-based calibration methods, commercial examples of which are Gelex Secondary Standards (Hach, Loveland, CO, USA) and ProCheck-S Solid standards (HF Scientific, Fort Meyers, FL, USA), may be a suitable alternative for a future version of this standard if they can be affordably and reliably manufactured in developing countries.

3.3.4 Validation and revalidation

In the AWQUA draft turbidity standard, validation is a follow-up process used to assess the goodness-of-fit of a calibration curve (especially a calibration curve that was derived using either of the alternative calibration methods described in the section above). Validation refers here to both initial factory validation by the manufacturer and to validation conducted by a qualified repair center (once such qualifications are detailed and certification procedures described). Revalidation refers to a validation carried out by the end user (assuming they are not the manufacturer nor a qualified repair technician).

To validate a calibrated turbidimeter, a set of at least four formazin suspensions (or EPA-approved secondary suspensions), spanning the calibration range and with values that are (roughly) orders-of-magnitude apart, must be measured by both the calibrated open-source turbidimeter and a well-calibrated commercial turbidimeter. Each such measurement must be a standard test batch. The results shall be evaluated in a Bland-Altman plot (aka Tukey mean-difference plot; Bland & Altman 1986). The nominal values of the suspensions must also be reported.

3.3.5 Drift

Drift is a source of systematic bias in the readings of a device and may be due to various factors including age of internal components or inadequate compensation for externally varying factors such as ambient temperature. For the AWQUA basic turbidity standard, drift shall be evaluated by taking three standard test batches at the prescribed interval (24 hours by default) of a suspension of constant turbidity value. The turbidity value of the test suspension must be evaluated before and after the drift test by measurement with a well-calibrated commercial turbidimeter.

3.3.6 Certification

Devices which meet the AWQUA basic turbidity standard can be certified by completing the documentation and testing procedures outlined in the AWQUA device development framework (see Section 3.2). The framework is intended to provide a documentation trail sufficient for self-certification of conformance with the requirements of this standard.

Additionally, no device may claim association with or imply favorable performance with respect to this standard unless that device has been fully evaluated against the requirements of this standard.

This includes language of casual association with this standard, such as “Designed to meet the AWQUA basic turbidity standard”; a proper designation of a well-tested device would be (e.g.) “Conformant to AWQUA basic turbidity standard”. The only permissible exception to this requirement is that devices in a recognized stage of the AWQUA device development framework may claim the partial or complete conformance with this standard conferred by completion of an AWQUA device development stage – e.g. “This device meets the performance requirements of an AWQUA Provisional turbidimeter”.

If a device is found to have spuriously implied association with the AWQUA Framework, or is found through testing to fail to meet its parameter-specific AWQUA standard, it is encouraged that such discovery be publicly reported to the device’s public repository.

3.3.7 Definitions

Standard read: A standard read shall consist of 50 replicate measurements of a water sample. This is a number chosen for convenience and speed of measurement. If ambient light levels are compensated by detecting the difference in turbidity readings with the light emitter turned on and off, a compensatory reading must be conducted for each of the 50 replicates.

Standard test batch: When considering inter-observer variation, the EPA turbidity regulations do not specify a required number of observations per observer – though observation counts in Table 1 of EPA Method 180.1 would suggest that 300-600 observations per observer are appropriate. In contrast, ISO 5725 (which provides the statistical backbone for ISO turbidity regulations) gives a well-defined and complex system for estimating numbers of observers and observations required for estimating observer accuracy and inter-observer agreement with a given level of confidence. A wholesale adoption of the ISO system by an open-source standard, however, would almost certainly amount to uncompensated appropriation of intellectual property. As a compromise, a standard test batch for the AWQUA basic turbidity standard shall consist of ten standard reads, yielding 500 total observations. For a well-calibrated commercial turbidimeter, which does not equip the user to select a number of replicate measurements per read events, ten read events shall comprise a standard test batch. (This exceeds the recommendation by turbidity expert Mike Sadar of a seven-reading minimum to determine the precision of a turbidimeter [Sadar 1999]).

3.4 Implementation issues

The AWQUA Framework is an attempt to facilitate the development of affordable water quality monitoring devices by providing detailed standards for device developers to meet, and a certification process which requires the publication of background research, details of development and testing efforts, and full explanations of the steps to produce compliant devices. The effort required to explain and detail such a framework is already large enough that turbidity was chosen as a sole regulatory focus in order to keep this dissertation tractable, but a regulatory framework alone does not make a functioning development ecosystem of usable devices – let alone get such devices into the hands of consumers. While issues of Framework implementation must generally be considered beyond the purview of the current work, the brief discussion below is included to acknowledge the broader contexts in which it is hoped the AWQUA Framework may eventually reside, and as food for thought.

3.4.1 Supporting policy environment

Democratization of environmental monitoring is a key aim of the AWQUA effort, and it is hoped that the AWQUA Framework can help guide the development of water quality monitoring devices that anyone can afford and anyone can use. Still, a particularly important potential application of AWQUA-compliant devices is state-mandated monitoring. The turbidity standard of the AWQUA Framework is targeted to permit monitoring at and below the WHO recommended turbidity level of 1.0 NTU prior to disinfection, which is lower than the national standards for many developing nations. To have a nation or set of nations permit the use of the AWQUA Framework as a turbidimeter certification standard, allowing the use of AWQUA turbidimeters at the Registered stage for regulatory monitoring, should be a primary benchmark of future implementation efforts.

3.4.2 Enforcement of the AWQUA Framework

Currently the AWQUA Framework has four key mechanisms with effects that extend beyond device development teams: (1) requirement of open-source licensing and publicly available documentation at every stage of device development; (2) stipulation of parameter-specific testing protocols (in Section 3.3), to facilitate independent testing of AWQUA devices; (3) language forbidding implicit association with AWQUA standards by products that are not developed to meet the AWQUA Framework; (4) A reporting mechanism to encourage the filing of issues in the public repositories of devices that spuriously claim association with the AWQUA Framework, or that have been found through independent testing to fail to meet their respective parameter-specific standard. The last of these is essentially a suggestion and places the burden of action on interested individuals. The AWQUA Framework does not have a government behind it to provide palpable consequences when regulatory requirements are ignored. A large and active community of volunteers could potentially provide the mechanism for finding and reporting AWQUA development projects that do not fully follow respective development requirements, but an AWQUA steering committee or similar centralized organization dedicated to helping the Framework grow and evolve would seem to be useful if not essential.

3.4.3 Curation and distribution of knowledge

Every stage of the AWQUA Framework requires open distribution of device design documentation. The requirement for audiovisual documentation at the Provisional and Registered stages is intended to push AWQUA devices to reach a broad audience. The static, publicly available copy of device and documentation required at each AWQUA development stage is intended to facilitate public feedback.

I would argue that beyond device development and distribution, a guiding goal of the AWQUA Framework should be the production of actionable monitoring information at affordable prices. Such a goal involves the communication of data collected by AWQUA devices and the analysis of such data by stakeholders, which in turn requires infrastructure and protocols for data communication. The AWQUA Framework attempts to simplify the first link in the data chain by requiring that all compliant device have removable memory and/or integrated data telemetry, and efforts such as the WASH For All water quality monitoring network in Honduras have demonstrated how data transmission networks can be run affordably (WASH For All 2017). Ensuring a functioning data transmission chain is beyond the purview of this dissertation but a critical issue for effective monitoring.

Another broader issue is the distribution of manufacturing knowledge, including the production quirks that may be found in the manufacture of specific monitoring devices, and the opportunities and challenges that arise when scaling manufacturing quantity.

3.4.4 Quality control

The AWQUA Framework addresses quality control first and foremost by requiring that device development teams openly share their work, but also through design aspects such as restricting the use of integrated circuit formats that require x-ray inspection for confirmation of proper assembly. It is likely that more design-oriented quality controls could be usefully employed. For example, non-destructive visual inspection of PCBs, to confirm that finished products match publicly shared specifications, could be further facilitated by stipulating that PCBs for AWQUA-compliant devices use no more than two signal layers and that electrical connections are not routed invisibly (e.g. underneath integrated circuits) whenever possible.

3.4.5 Training and certification of manufacturers

The broader issue of quality control with regards to manufacturing deserves particular attention. A key motivation behind the AWQUA Framework is to make possible the globally distributed manufacture of monitoring tools essential for public health, and in this respect I would argue the AWQUA turbidity standard is significantly more amenable than the EPA and ISO turbidity standard. For regulation to translate to manufacturing, however, device manufacturers must know how to follow AWQUA requirements and how to reliably construct AWQUA-compliant devices. Training of manufacturers for small- or medium-scale production of AWQUA-compliant devices, and the certification of such manufacturers and their factories, are critical links that connect directly to the work in this dissertation.

3.5 Technical demonstrations of monitoring device development guided by the AWQUA Framework

The draft framework outlined above contains two main parts. The first part provides a general process for open-source water quality monitoring device development. The second part provides a turbidimeter performance standard tailored for open-source device development, which is adapted from EPA and ISO turbidity standards (addressing issues in these standards that were raised in Chapter 2) and is targeted to WHO monitoring levels.

Chapters 4 – 7 provide examples of open-source drinking water quality monitoring devices, in various stages of the AWQUA Framework. These devices were largely developed alongside, and in some respects before, this framework was developed. Particularly, the device detailed in Chapter was developed entirely before the development of the AWQUA Framework and helped inform its development. The devices in these chapters are evaluated at various points in the documentation process. Chapter 4 presents the Affordable Open-Source Turbidimeter, which is evaluated as a Phase II Prototype Design under the AWQUA Framework. Chapter 5 presents the Black Box handheld turbidimeter, which is evaluated as a Phase II Prototype Design. Chapter 6 presents the Monocle inline turbidimeter, a submersible device which is evaluated as a Phase III Prototype Design. Finally, Chapter 7 presents the Jar Opener, a jar tester which is evaluated as a Proposed Design.

The device presented in Chapter 4 was previously published in the peer-reviewed, open-access journal Sensors in an article titled An Affordable Open-Source Turbidimeter (Kelley et al. 2014). Excerpts from that article are presented (with attribution) in Chapter 4. Chapters 4 – 7 are presented with a common, simple format to provide an example of the economical, modular structure that is expected of documentation efforts under the AWQUA Framework. The ten-part structure of this common format is:

Section 1: Foreword

Section 2: Introduction to the type of monitoring tool addressed

Section 3: Existing standards for this type of tool

Section 4: Commercial versions of this type of tool

Section 5: Open-source versions of this type of tool

Section 6: Justification for a new open-source design of this type of tool

Section 7: Presentation of new open-source design

Section 8: In-depth AWQUA Framework review of the design in Section 7

Section 9: Summary of Section 8

Section 10: References

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Chapter 4: Handheld turbidimeter for water quality monitoring in low-resource settings

4.1 Chapter foreword

The chapter details an open-source turbidimeter that was developed before the AWQUA device development framework outlined in the previous chapter. The device detailed herein should not be considered suitable for typical regulatory monitoring purposes but is evaluated as a Phase II Prototype to help illustrate how the AWQUA turbidity standard and device documentation process can help make turbidimeter design shortcomings more apparent than they might otherwise be if the device is simply presented in a peer-reviewed scholarly article. Please note that section 4.7 contains text from the manuscript An Affordable Open-Source Turbidimeter (*Sensors* 14.4 (2014): 7142-7155), on which the author of this dissertation was lead author.

4.2 Introduction to handheld turbidity monitoring

This is addressed in Section 2.1.

4.3 Existing standards for handheld turbidity monitoring

The two key design standards for turbidimeters are EPA Standard Method 180.1 (EPA 1993), promulgated by the US Environmental Protection Agency, and ISO 7027:2016 (ISO 2016), promulgated by the International Organization for Standardization (ISO). Section 2.4 explores relevant details of these standards. A draft turbidity standard designed to facilitate the development of open-source turbidimeters is detailed in Chapter 3.

4.4 Commercial handheld turbidimeters

This is addressed in Sections 2.5 and 2.7.

4.5 Existing open-source handheld turbidimeter designs

This is addressed in Section 2.6.

4.6 Why make a new open-source handheld turbidimeter design?

As mentioned in Section 2.6, there currently appear to be no open-source turbidimeter designs that are ready for production, and none that have demonstrated compensation for the effects of ambient temperature variation on LED brightness. Further, there is apparently no open-source design that is demonstrated to meet EPA or ISO nephelometry standard. As a separate issue, the shortcomings of these standards are documented in Sections 2.7 and 2.8.

4.7 Preliminary effort and proof of concept: The Affordable Open-Source Turbidimeter

4.7.1 Design Elements

An open-source turbidimeter (see Figure 4.1a) was built using off-the-shelf electronic components and 3D-printed hardware. The circuit design employs an 8-bit, 20 MHz microprocessor (Model ATMega328P-PU; Atmel, San Jose, CA, USA). The microprocessor was programmed in the C-based Arduino language. The principal housing components—a two-part case and a cylindrical cuvette holder—were made with a commercial 3D-printer (Model Replicator 2×; MakerBot, Brooklyn, NY, USA), although an open-source printer could have also served the purpose. The build envelope of the case measures 205 mm long, 91 mm wide, and 55 mm tall. The cuvette holder houses a near-infrared (860 nm) light emitting diode (LED) and a light-to-frequency sensor (Model TSL230R; TAOS, Plano, TX, USA), placed 90 degrees apart in a "single-beam" design (see Figure 2.1a). The light-to-frequency sensor outputs an electrical pulse train with frequency corresponding to the intensity of detected light (TAOS 1992). The microprocessor sums pulse counts from the sensor in one-second intervals and converts these sums to turbidity values using an empirically determined calibration routine (detailed below) stored in persistent memory. Light-to-frequency sensors have been noted as potentially suitable photodetectors in two patents for novel turbidimeter designs (Smith et al. 1996, Taylor & Bull 1998). The TSL230R in particular has been used to provide turbidity sensing for process control in dishwashers (Badami & Chbat 1998), and to determine the biological oxygen demand (BOD) of aqueous solutions (Anzalone et al. 2013). To our knowledge this study represents the first publicly available peer-reviewed characterization of an affordable turbidimeter based on a light-to-frequency sensor.

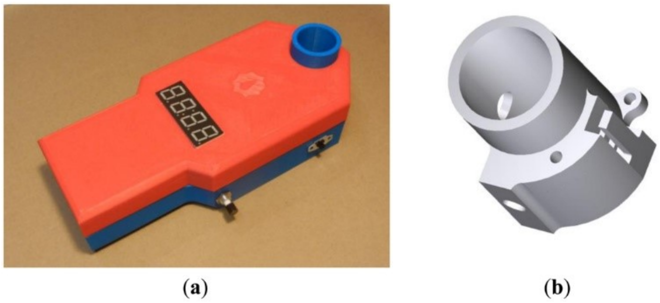


Figure 4.1. Open-Source Turbidimeter: (a) external view, (b) image of cuvette holder.

Data are displayed on an inexpensive four-digit, seven-segment display panel. The device is powered by four AA batteries and has a sliding power switch and a momentary contact push button on its exterior to initiate sampling and device re-calibration. Battery drain tests indicate that the device can handle hourly sampling for three months on four alkaline AA batteries. This open-source turbidimeter can be built using parts valued at less than $25 and with approximately 3 hours of labor. The model used for these experiments, which employs various hardware conveniences for ease of experimentation (such as a solderless breadboard) has parts costing roughly $35 and can be constructed in 45 min. All schematics and code required to build this open-source turbidimeter are provided in the Supplementary Materials section; the code is copyrighted for public use through the GNU GPLv3 license. The electronic components of the open-source turbidimeter are depicted in Figure 4.2 and described in detail in the Supplementary Materials.

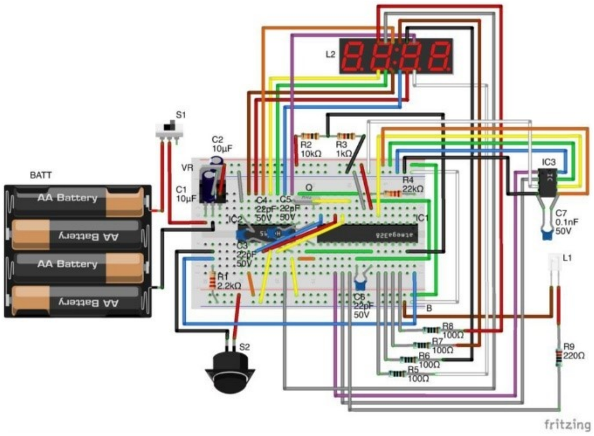


Figure 4.2. Wiring diagram for the open-source turbidimeter.

4.7.2 Assessment procedure and performance data

To convert sensor output to report turbidity, it was necessary to empirically match the sensor's pulse train frequency to corresponding NTU values, and to store this calibration routine in persistent memory of the microprocessor. Nephelometry standards from both the EPA (Standard Method 180.1) and the International Organization for Standardization (ISO 7027:2016) state that turbidimeters should be calibrated against aqueous suspensions of the polymer formazin, or an approved formazin alternative (EPA 1993, ISO 2016). Because formazin is a hazardous chemical that is relatively difficult to use on a routine basis, an alternative was sought. To avoid the extensive cost of purchasing commercially available formazin alternatives (which must be purchased at specified turbidities because they become unstable if diluted), series of 25 stable colloidal suspensions by diluting hydrophilic cutting oil with distilled water were created, following an approach previously employed and reported by Lambrou et al. (2010).

For calibration of the open-source instrument, each of the 25 cutting oil suspensions was stored in a quartz cuvette and measured eight times with the open-source turbidimeter and eight times with a commercial ratio-based turbidimeter purchased as the standard of comparison for this experiment (MicroTPI model; HF Scientific, Fort Meyers, FL, USA). Concentrations, measured with the commercial instrument, ranged from roughly 0.01 to 1100 NTU. Averaged readings from the open-source turbidimeter for each cutting oil suspension were regressed on averaged readings from the commercial device to develop the calibration curve. Since a primary objective of this experiment is to affordably replicate the behavior of a commercial turbidimeter, individual readings of cutting oil suspensions taken with the open-source turbidimeter were transformed with the calibration curve, and compared to averaged readings from the commercial turbidimeter—these averaged readings from the commercial turbidimeter taken as surrogates for the true turbidity values of the 25 suspensions. The slope and intercept constants of this calibration routine were programmed into the microprocessor of the open-source instrument, and the commercial and calibrated open-source turbidimeters were then tested against five reference turbidity standards (0.02, 1, 10, 100, 1000 NTU, respectively) of an EPA-approved formazin alternative (StablCal, purchased from Fisher Scientific, Pittsburgh, PA, USA). Each reference turbidity standard was measured eight times with each of the turbidimeters. All suspensions and standards were re-measured after 24 h to test for colloidal stability.

Calibration data from the two instruments are presented in Figure 4.3. Two of the 200 commercial turbidimeter readings in the calibration dataset were discarded because they were implausibly high for the given sample. The dataset is monotonic across the range of investigation (see Figure 4.3a) and is approximated well by four linear regressions connected by three transition points (see Figure 4.3b–e). These transition points were visually selected and are discussed further below.

One regression line (Figure 4.3b) covers four concentrations of cutting oil suspension; the other three regression lines (Figure 4.3c–e) cover seven concentrations each. The regression lines fit the observed values very well above 0.5 NTU (R2 = 0.9990), and nearly as well below 0.5 NTU (R2 = 0.9977); slope and intercept values are given in Figure 4.3. Regression residuals were within ± 5% for all data points (and within ± 3% for 23 out of 25 data points). The open-source turbidimeter was thus calibrated, and the calibrated data points were compared to averaged commercial turbidimeter readings to assess data spread. Out of 200 measurements of the open-source device, 192 lie within ± 3% or ± 0.3 NTU (whichever is larger) of the averaged measurement of the commercial device for the respective cutting oil suspension. The remaining eight measurements lie within ± 3.5%, and all measurements for the four suspensions under 0.5 NTU are within ± 0.01 NTU. There were no spatial patterns in the residuals of any regression line, and all p-values were less than 0.001. Generally, precision scaled negatively with turbidity value, and accuracy was worse near the transition points between regression lines. The open-source turbidimeter was also tested without a sample in the cuvette holder; both with the light source turned on (frequency: 168 Hz) and turned off (frequency: 0 Hz). After thus calibrating the open-source turbidimeter, both this instrument and the commercial device were used to measure five EPA-approved non-formazin turbidity standards, eight times each, with results shown in Figure 4.4. The mean, standard deviation, and root-mean-square error of each set of measurements are presented in Table 4.1.

The analysis indicates that the open-source turbidimeter provides a reasonable approximation of results given by a commercial handheld model over the range of 0–1,000 NTU. This is remarkable given that the open-source device can be built for roughly 4% of the cost of the commercial model. Construction requires only a rudimentary knowledge of electronics and access to basic tools and a soldering iron. Since the open-source turbidimeter uses common low-cost electronics components (no part over $6 and only three above $2; see Supplementary Materials), the device can be affordably repaired by owners with access to spare parts. As the construction and improvement of the prototype turbidimeter is an open-source endeavor, complete instructions and parts lists are hosted online at WASH For All (2017). One important update to the open-source turbidimeter incorporated after these experiments is an internal temperature sensor (LM35; Texas Instruments, Dallas, TX, USA) to measure ambient temperature changes (which can be significant outside of a climate-controlled laboratory) and firmware edits to compensate for thermal effects on the relative intensity of the LED.

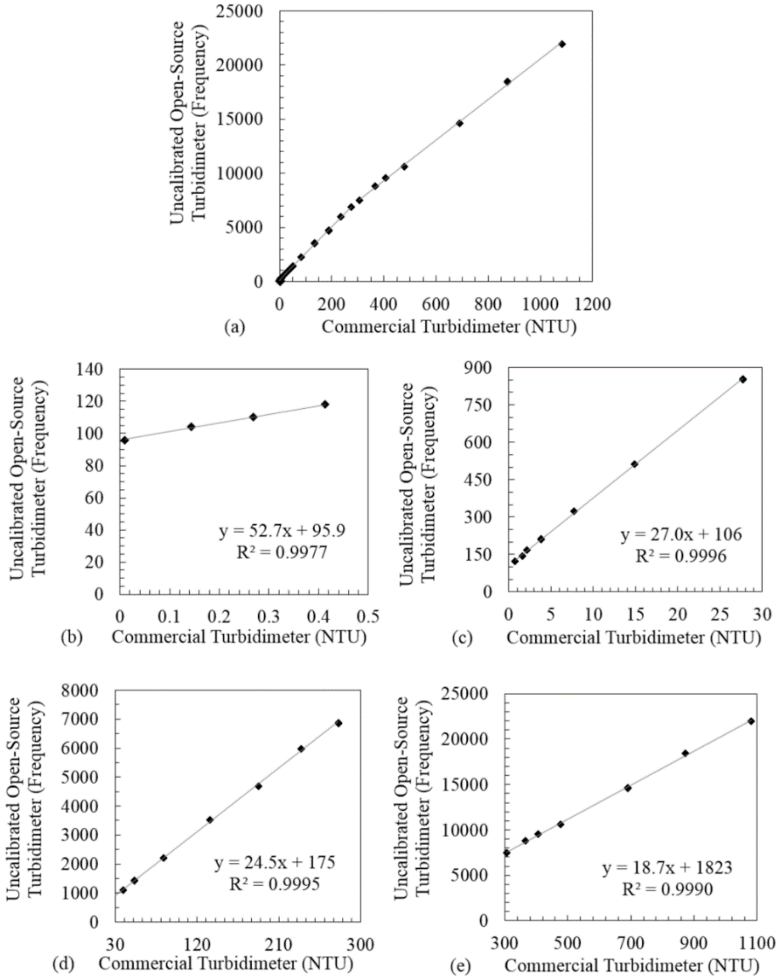


Figure 4.3. Comparison of averaged open-source turbidimeter and commercial turbidimeter measurements of 25 cutting oil suspensions, overall (a) and in four sub-regions: (b) 0–0.5 NTU; (c) 0.5–30 NTU; (d) 30–300 NTU; (e) 300–1,100 NTU.

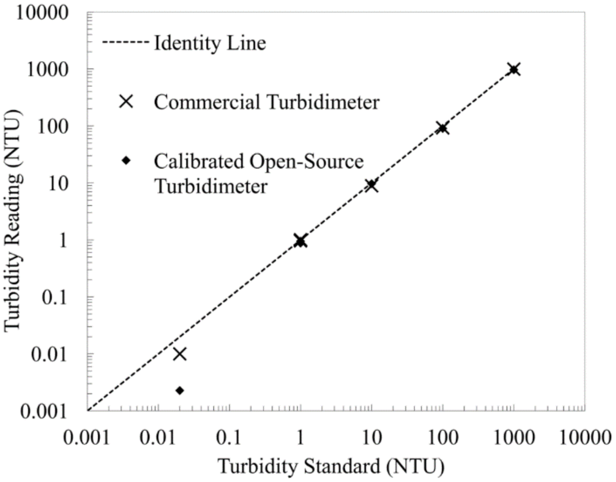
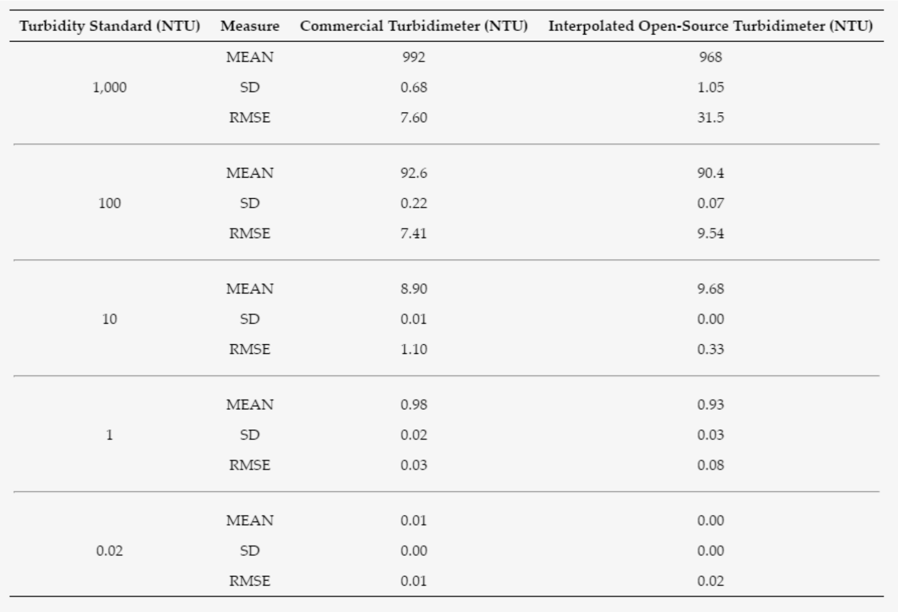


Figure 4.4. Commercial and open-source turbidimeter measurements of five non-formazin turbidity standards.

Table 4.1. Mean, standard deviation (SD), and root-mean-square error (RMSE) of commercial and open-source turbidimeter readings of five non-formazin turbidity standards.



Turbidity Standard (NTU)	Measure	Commercial Turbidimeter (NTU)	Interpolated Open-Source Turbidimeter (NTU)
1,000	MEAN	992	968
	SD	0.68	1.05
	RMSE	7.60	31.5
100	MEAN	92.6	90.4
	SD	0.22	0.07
	RMSE	7.41	9.54
10	MEAN	8.90	9.68
	SD	0.01	0.00
	RMSE	1.10	0.33
1	MEAN	0.98	0.93
	SD	0.02	0.03
	RMSE	0.03	0.08
0.02	MEAN	0.01	0.00
	SD	0.00	0.00
	RMSE	0.01	0.02

Both the open-source and commercial turbidimeters detected the lowest turbidity standard to within ± 0.02 NTU (as stipulated by EPA certification requirements), however it should be noted that random thermal fluctuations can induce apparent turbidity and influence measurements of turbidities this low. A logical next step in this research will be to better characterize performance of the open-source turbidimeter over the range of 0–1 NTU using more EPA-approved non-formazin standards. It is likely though that detection accuracy and precision in this range are of relatively minor concern for communities that are struggling, both financially and technically, to meet stringent turbidity standards. This unfortunate reality is reflected in the relatively high turbidity limits set by many developing countries—e.g., India at 1 NTU (BIS 2012), and Honduras at 5 NTU (RADWS 2005).

Both the open-source and commercial turbidimeters are imperfect devices. As the open-source device is calibrated against the commercial model, the uncertainty of the commercial model (± 2% or ± 0.1 NTU for 0–500 NTU, ± 3% for 500–1,000 NTU) should affect the accuracy of the open-source model. An attempt was made to minimize this potential source of error by averaging replicate readings of the commercial model. The evaluation of both devices with EPA-approved non-formazin standards of known turbidity is thus an important external validation, but the relative agreement of the two devices is the most important message. Thus, while the calibrated open-source turbidimeter appears to outperform the commercial turbidimeter in detecting the value of the 10 NTU standard, this should be taken as coincidental—logically the open-source turbidimeter cannot best the source of its calibration. It is worth noting that both devices measured values lower than the stated values of the turbidity standards in all cases. It is possible that the turbidity standards, although newly purchased from a reputable vendor, may have degraded slightly since formulation. It is also possible that the commercial turbidimeter, although newly purchased from a reputable vendor and calibrated in the factory, may have been slightly off. All cutting oil suspensions and turbidity standards were re-measured after 24 h; none showed drift beyond 0.5% or 1.0 NTU (whichever is smaller) of the respective averaged original readings.

The choice of using multiple regression regions to characterize the calibration dataset presented in Figure 4.3 was motivated by a slight non-linearity in the dataset (visually most apparent at roughly 300 NTU; see Figure 4.3a). This may be due to the fact that the open-source turbidimeter uses a single-beam design while the commercial model uses a ratio design, since the linear performance of a single-beam turbidimeter—using only a scattered-light detector—necessarily diminishes with increasing turbidity earlier than that of a ratio turbidimeter, which normalizes scattered light readings with transmitted light readings. The transition values which ensure continuity of the four-part regression equation (0.4 NTU, 26.4 NTU, and 287.8 NTU, respectively) differ slightly from the transition points chosen before regression analysis; the former are used in the calibration function of the software (Supplementary Materials). Exploring the response of the open-source turbidimeter to precisely measured formazin dilutions, and in particular assessing the maximum value of the device's performance range, are important next steps. Still, the evidence presented here indicates that a single-beam turbidimeter employing a light-to-frequency sensor can usefully measure turbidity over a range of 0–1,000 NTU, provided that multiple linear regression ranges are used to convert raw sensor data to turbidity values.

4.7.3 Acknowledgments

This project was supported financially through an NSF IGERT grant (DGE-1069213), and an EPA P3 grant (OSP# 69442/A001). I wish to thank Dan Naiman (Johns Hopkins University) for his advice, and also thank Alan Stone (Johns Hopkins University) and Sushant Murthy (undergraduate, Johns Hopkins University) for their assistance.

4.7.4 Author and developer contributions

Christopher Kelley and Cornell University undergraduate engineering student Alexander Krolick wrote (with equal contributions) the first draft of the manuscript. Johns Hopkins University undergraduate engineering students Daniel Kahn, Alison Burklund and Logan Brunner contributed the graphs and tables. William Ball contributed to the experimental design. All authors contributed to the writing and editing of the manuscript.

Christopher Kelley developed the Affordable Open-Source Turbidimeter, which was improved in several iterations through the assistance of Alexander Krolick. Alison Burklund and Logan Brunner tested the device extensively.

4.7.5 Supplementary materials for the Affordable Open-Source Turbidimeter

Supplementary materials may be found in Appendix A.

4.8 AWQUA Framework Review of the Affordable Open-Source Turbidimeter

The Affordable Open-Source Turbidimeter offers a very simple turbidity sensing setup, which can be quickly and manually assembled, largely by hand and for very little money. As such it may be of good use in the classroom for environmental science or engineering lessons. As a compliance monitoring device it falls short; it is too difficult to keep in calibration because of unaddressed issues in its design such as temperature compensation, voltage stability, and case stiffness. The AWQUA basic turbidity standard was in fact written in part with lessons learned from the development of the Affordable Open-Source Turbidimeter and the Black Box handheld turbidimeter, detailed in Chapter 5, is considered a replacement for the Affordable Open-Source Turbidimeter. Nonetheless, and for all purposes an illustration example, I provide below an AWQUA Framework review of the Affordable Open-Source Turbidimeter.

This is a brief walkthrough of the documentation requirements under the AWQUA development guidance framework (which is detailed in Section 3.2). The Affordable Open-Source Turbidimeter is evaluated below as an AWQUA Phase II Prototype device.

User:

Proposed

(U1) A description of the population of end users envisioned (e.g. "rural communities in developing countries").

> This is superseded by (U2).

Prototype – Phase I

(U2) Any new or revised information about the envisioned end-user population description from (U1).

> The Affordable Open-Source Turbidimeter was originally designed to address water quality monitoring needs in developing countries. After testing and evaluating the device, a more appropriate target audience would be students and educators, for whom the Affordable Open-Source Turbidimeter might serve as a useful introductory tool for the fabrication and operation of low-cost environmental monitoring equipment.

Prototype – Phase II

(U3) A conservative estimate of how frequently calibrations should be performed, based on available information on the measurement mechanism and the testing data for the specific device.

> As this device is intended to be constructed by the end user, and is not intended for regulatory purposes, it is up to the end user to decide how frequently to calibrate the device. Given the influence of background light, voltage level, and ambient temperature on the measurement mechanism, a daily three-point calibration in a given measurement range of interest (see Subsection 4.7.2) is recommended on days when the device is used.

Sampling:

Proposed

(S1) A summary of any known sampling issues which may affect the measurement process or the operation of the Proposed device (e.g. “when conducting turbidity measurements cuvettes must be wiped and dried, both to remove any dirt from the outside of the cuvette and to dry the cuvette and prevent damage to the device electronics”).

This is superseded by (S2).

Prototype – Phase I

(S2) Any new or revised sampling issues encountered since (S1).

> During testing it was noted that the orientation of the cuvette in the cuvette holder significantly affected the readings produced by the device. This seems to be due to the large ratio of background light reading (the light hitting the sensor when the cuvette is empty) to the signal (the light hitting the sensor due to turbidity in the cuvette), and the resulting fact that small percentage changes of the total light (background plus signal) due to cuvette orientation have a large effect on readings of the signal. This can be in the current design addressed by calibrating the device for use with a single cuvette, and carefully placing the cuvette in the cuvette chamber with the same orientation for every reading. For future versions of this device, however, a more prudent solution would likely involve better shielding and focusing of the LED light beam.

Prototype – Phase II

No information required.

Environment:

Proposed

(E1) A description of the intended geographical areas where device use is envisioned.

This is superseded by (E5).

(E2) Existing literature on the applications of the proposed mechanism for measuring the intended parameter;

This is addressed in Section 2.1.

(E3) A listing of relevant, currently available commercial monitoring devices;

This is addressed in Section 2.5.

(E4)* An explanation as to why the proposed device should be developed and employed (e.g., rather than an equivalent existing device being employed).

This is addressed in Section 4.3 and is discussed more broadly in Chapter 2.

Prototype – Phase I

(E5) Any new or revised information for (E1) on the intended geographical areas where device use is envisioned.

Although originally designed for outdoor monitoring in tropical and temperate climate, the lack of adequate temperature compensation makes the Affordable Open-Source Turbidimeter better suited for a climate-controlled classroom or laboratory.

Prototype – Phase II

(E6) A "Cost at Scale" (CAS) BOM with suggested suppliers and hardware costs for manufacturing runs of 1 to 1,000 units in decades.

X This was not conducted for the Affordable Open-Source Turbidimeter, as the device is considered unsuitable for manufacturing at scale for regulatory purposes.

Device:

Proposed

(D1) A statement of the intended form factor, power source, use setting, data transmission chain, and actuation mode of the proposed device.

This is addressed in Section 4.5.1.1 and Appendix A.

(D2) A detailed sketch of the proposed monitoring device should be documented, which provides visual reference to each of the items identified in (D1).

This is superseded by requirements in Prototype stage.

Prototype – Phase I

(D3)* Circuit description, consisting of a schematic, and either a PCB layout (in, e.g., EagleCAD) or breadboard layout (in, e.g., Fritzing).

This is addressed in Figure 4.2 and Figure A2.

(D4)* A Logic of Operations description, detailing how the device will interface with a user, and take, calculate, store, display, and transmit measurements.

This is available at https://github.com/AWQUA/basic-handheld-turbidimeter.

(D5)* A diagram of the structural components of the measurement mechanism (e.g. a cuvette chamber or optical window).

This is addressed in Figure A3.

(D6) A Bill of Materials (BOM), detailing the electrical components of the measurement mechanism.

This is addressed in Table A1.

(D7)* Datasheets for key electrical and structural components.

This is available at https://github.com/AWQUA/basic-handheld-turbidimeter.

Prototype – Phase II

(D8) Circuit design files (e.g. EagleCAD BRD/SCH files, as well as CAM files in Gerber RS274-X format).

This is available at https://github.com/AWQUA/basic-handheld-turbidimeter.

(D9) Firmware code in a common language (e.g. Arduino, C, MicroPython, MBED, FreeRTOS).

This is addressed in section A.1.1.3.

(D10) Software code, if any.

The Affordable Open-Source Turbidimeter uses no software.

(D11) A description of the data storage schema used, if any.

The Affordable Open-Source Turbidimeter uses no data storage schema.

(D12) A description and link to any firmware or software libraries used to build the device's code.

GSM library (GSM.h), which is included in the core Arduino libraries, is detailed at https://www.arduino.cc/en/Reference/GSM

Pin Change Int library (PinChangeInt.h), used to give software-defined interrupt capability on arbitrary GPIO pins for a variety of ATMega-family microprocessors, is detailed at https://playground.arduino.cc/Main/PinChangeInt.

EEPROM library (EEPROM.h), which abstracts read and write operations to the 1KB of internal EEPROM onboard ATMega-family microprocessors, is detailed at https://www.arduino.cc/en/Reference/EEPROM.

EEPROM Anything (EEPROMAnything.h), which expands the variety of variable types that can be written to onboard EEPROM via the EEPROM library, is detailed at https://playground.arduino.cc/Code/EEPROMWriteAnything.

(D13) Design files of internal structural elements, if any, in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD).

This is available at https://github.com/AWQUA/basic-handheld-turbidimeter.

(D14) Design files of internal structural elements, if any, in a common interchange format (e.g. STL, DXF).

This is available at https://github.com/AWQUA/basic-handheld-turbidimeter.

Measurement:

Proposed

(M1) A description of the parameter to be measured, and an explanation of the relevance of this parameter to water quality testing.

This is addressed in Section 2.1.

(M2) A description of the measurement mechanism to be used, as well as other common measurement mechanisms that have been or can be used for the parameter indicated, including a brief comparison of the advantages and disadvantages of the proposed measurement mechanism relative to the other mechanisms listed.

The Affordable Open-Source Turbidimeter uses nephelometry, a turbidity measurement technique involving a ninety-degree separation of light emitter and light detector that is addressed in Section 2.1. Other turbidity measurement techniques, such as forward scatter, attenuation, and backscatter, vary the angle between emitter and detector. Nephelometry is the most common turbidity sensing setup for handheld turbidimeters, offering a more linear and sensitive detection response at low turbidity than other methods (Sadar 1999).

Prototype – Phase I

No information required.

Prototype – Phase II

(M3) A description of the device calibration procedure and re-calibration procedure (if different).

This is addressed in Section 4.5.1.2.

(M4) A description of the procedure by which calibrations will be verified and the measurement precision and accuracy of the device ascertained. This should include consideration for how to measure drift over time and temperature ranges (and appropriate ranges for any other confounder variable identified in [L3] below).

X This was not fully specified for the Affordable Open-Source Turbidimeter. A basic validation procedure is described in Section 4.5. Device performance data provided by independent testing partners suggested both the inadequacy of this basic validation procedure and the unsuitability of the turbidimeter designed herein. A subsequent alternate design was undertaken (see Chapter 5).

Interactive:

Proposed

(I1)* Descriptions of devices at all stages of the AWQUA development framework must be published in a publicly available online repository (e.g. GitHub).

This is available at https://github.com/AWQUA/basic-handheld-turbidimeter.

Prototype – Phase I

No information required.

Prototype – Phase II

(I2) Following completion of all other requirements in Phase II, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

> Device design was detailed at http://www.mdpi.com/1424-8220/14/4/7142 and left available, unedited, for comment.

Legal:

Proposed

(L1) Documentation of primary measurement standards and testing procedures (e.g. EPA, ISO, WHO), if any, for the proposed pair of analyte and measurement mechanism;

> Nephelometer standards are described in EPA Method 180.1 (EPA 1993) and ISO 7027:2016 (ISO 2016). Specific details of these standards are discussed at length in Section 2.4.

(L2) A statement acknowledging and crediting all members of the device development team for their contributions.

> This is addressed in Sections 4.5.4 and 4.5.5.

Prototype – Phase I

No information required.

Prototype – Phase II

(L3)* The specific water quality monitoring standard or guideline for which the Prototype device is intended to be a suitable measurement device.

> The draft AWQUA basic turbidity standard is put forward in Chapter 3 as an alternative to ISO 7027:2016 and EPA Method 180.1 two standards for open-source turbidimeters; this particular device was not developed to meet the draft AWQUA basic turbidity standard and has been superseded by the device detailed in Chapter 5.

Quality assurance / quality control:

Proposed

No information required.

Prototype – Phase I

(Q1) Proof of operational measurement utility must be provided in the form of a basic measurement data set, along with a summary of how the device was operated to obtain the data.

> This is superseded by (Q2).

Prototype – Phase II

(Q2) Calibration data, from a calibration procedure conducted according to the water quality monitoring standard selected in (L3).

> This is addressed in Figure 4.3.

(Q3) Validation data, from a validation procedure conducted according to the water quality monitoring standard selected in (L3).

> This is addressed in Figure 4.4.

(Q4) Drift data, showing the consistency of readings taken with the same Prototype device over time, and across the range of ambient conditions for measurement confounder variables identified in (M4) (or as required by the analyte-specific standard and appropriate for the intended environment of use).

> **X** These data were not fully gathered for the Affordable Open-Source Turbidimeter. Drift tests across operating voltage and ambient light level and temperature indicated large drift.

Construction, Affording, Maintenance, Operation (CAMO) summary:

Proposed:

For the Proposed phase, the CAMO summary should outline what areas of the world – and what measurement niche – the device is intended for use in, and list any foreseen design or manufacturing issues.

> Due to the design and performance limitations outlined above, the practical applications of the Affordable Handheld Turbidimeter may be limited to educational and training use (or for use when all better options for electronic turbidity monitoring are unavailable). The low cost and open design of the device remove many of the traditional barriers for environmental monitoring and allow the device to be reasonably calibrated by non-experts (assuming that the constituent components can be gathered). One device issue worth noting is the requirement of the current design for a 3D printer – while these have much lower costs and operating requirements than other common tools for physical object manufacturing (such as laser cutters and CNC mills; lower-cost 3D printers may be no more expensive than band saws and drill presses) it nevertheless imposes a much more significant production bottleneck than the need for a soldering iron. If the device is being

built purely for educational purposes though, it may be suitable to omit the 3D-printed case entirely.

It should also be noted that while the device is designed to be entirely based around “through-hole” components (with connections that pass through the circuit board), the TSL230R light-to-frequency sensor chip is no longer manufactured in through-hole form factor. A “surface-mount” version of the sensor (with connections that sit on the circuit board), the TSL230RD, is readily available and may be substituted in this device design with an appropriate adapter.

4.9 AWQUA Framework Summary of Affordable Open-Source Turbidimeter

The Affordable Open-Source Turbidimeter is a “bare-bones”, low-cost device that may be well-suited to teaching environmental monitoring and water treatment monitoring. This device was evaluated as a Phase II Prototype. The development team for this device failed to complete requirements (E6), (M4), and (Q4). The device has not met the requirements for a Phase II Prototype, but has met all of the requirements for a Phase I Prototype. Development effort on this device has been terminated, but the full set of documentation for this device remains publicly available.

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Chapter 5: An AWQUA handheld turbidimeter

5.1 Chapter foreword

The purpose of this chapter is to detail an open-source turbidimeter (a device to measure the cloudiness of water) and to evaluate this device with respect to the AWQUA device development framework detailed in Chapter 3. This evaluation is presented in Section 5.8 in a compact, modular, non-narrative fashion that is the intended format for AWQUA Framework documentation. To meet the expectations of a more traditional dissertation chapter, key points of documentation for the AWQUA Framework are presented in Sections 5.2 through 5.7 in a scholarly narrative format (with reference to preceding Sections and Chapters if necessary material has already been detailed elsewhere in the dissertation).

5.2 Introduction to handheld turbidity monitoring

This is addressed in Section 2.1.

5.3 Existing standards for handheld turbidity monitoring

The two key design standards for turbidimeters are EPA Standard Method 180.1 (EPA 1993), promulgated by the US Environmental Protection Agency, and ISO 7027:2016 (ISO 2016), promulgated by the International Organization for Standardization. Section 2.4 explores relevant details of these standards. A draft turbidity standard designed to facilitate the development of open-source turbidimeters is detailed in Chapter 3.

5.4 Commercial handheld turbidimeters

This is addressed in Sections 2.5 and 2.7.

5.5 Existing open-source handheld turbidimeter designs

This is addressed in Section 2.6.

5.6 Why make a new open-source handheld turbidimeter design?

The root motivation for this design is addressed in Chapter 2 and Section 4.6. This particular device design is intended to be an update of the Affordable Open-Source Turbidimeter (Chapter 4) that is compliant with the AWQUA device development framework and the AWQUA basic turbidity standard.

5.7 The Black Box handheld turbidimeter

5.7.1 Design Elements

Structure: The Black Box handheld turbidimeter uses a double-walled cuvette holder made of laser-cut 3mm-thick black acrylic.

At present, the prototype does not encase the main circuit board (which contains the users interface) or batteries. This must be addressed before the device can progress to a Phase III Prototype under the AWQUA Framework.

Power: The device is powered by a 3.7V, 2200 milliamp-hour (mAh) lithium-ion battery. A dedicated 4.2V charge management chip and a microUSB port allow the lithium-ion battery to be charged from a 5-7V DC source – this allows recharging via a solar power charger or a standard USB port (the latter by using the typical power cable for Android-compatible phones). Additionally, a 3V, 130 mAh lithium coin battery is used to provide back-up power for an external, always-on clock.

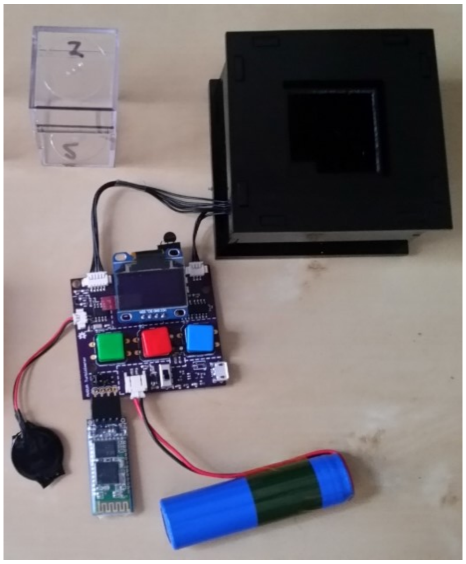
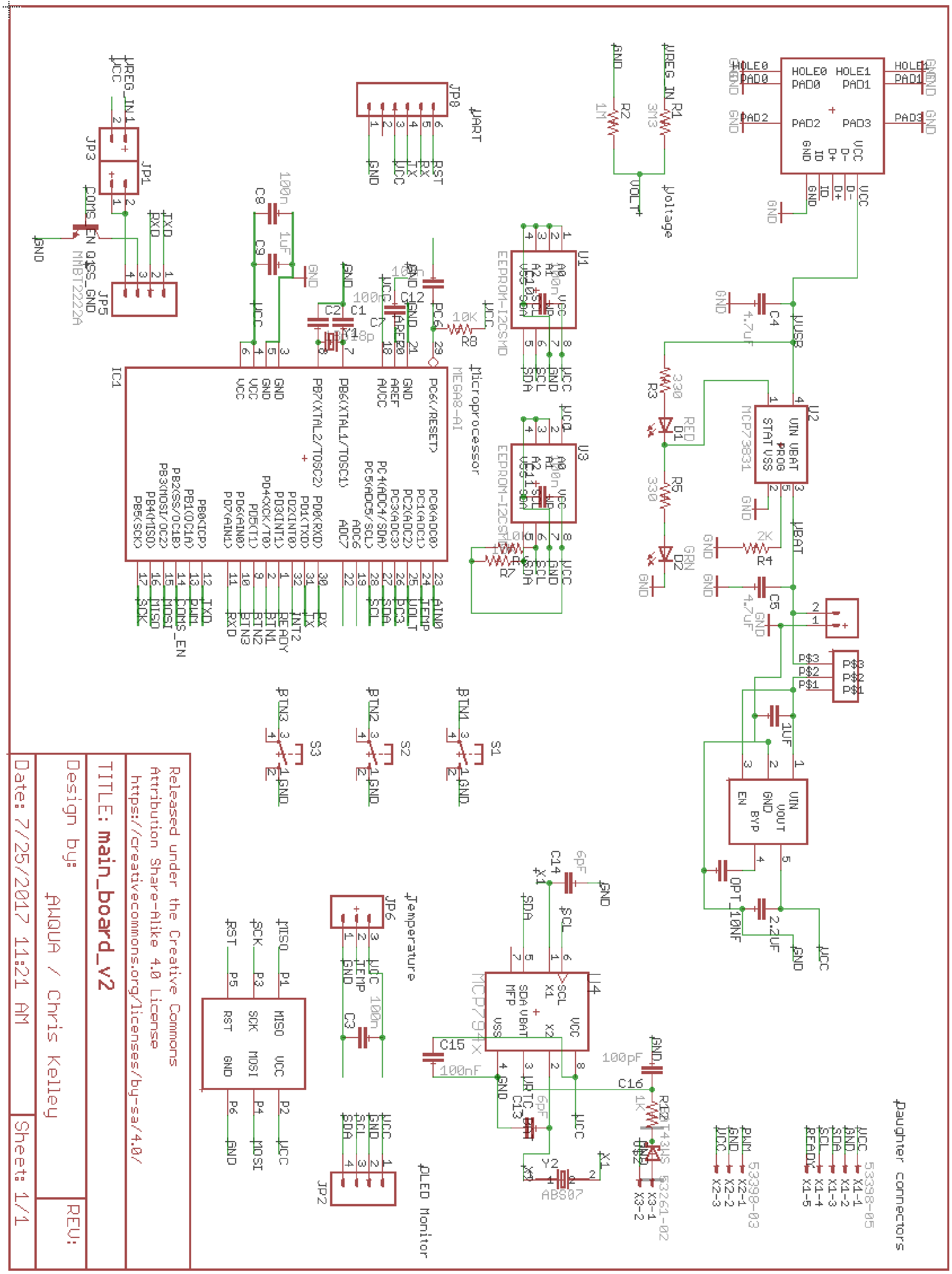


Figure 5.1. The Black Box handheld turbidimeter.

Microprocessor: The device uses an 8-bit, 16MHz microprocessor (ATMega328P) manufactured by Atmel (San Jose, CA, USA), with an external high-precision (+/-20ppm frequency error) oscillator.

Control: The control demands of this device are simple: (1) accept user commands as supplied, (2) collect ancillary data (timestamp, operating voltage, ambient temperature), (3) collect turbidity readings and ambient light readings alternately, (4) perform statistics on collected batch of turbidity readings after subtracting ambient light readings (see *Data* section below), (5) transform turbidity readings and statistics from raw units to NTU by interpolating against calibration curve, (6) display and store data as appropriate for usage mode (see the *Reporting* requirements of Section 3.3.2).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Design by: AWQUA / Chris Kelley
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JP5
JP6
JP2
Temperature
OLED Monitor
Voltage
VOLT
VUSB
VBAT
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S2
S3
BTN1
BTN2
BTN3
GND
VCC
REG_IN
Y2
ABS07
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53261-02
MMBT2222A
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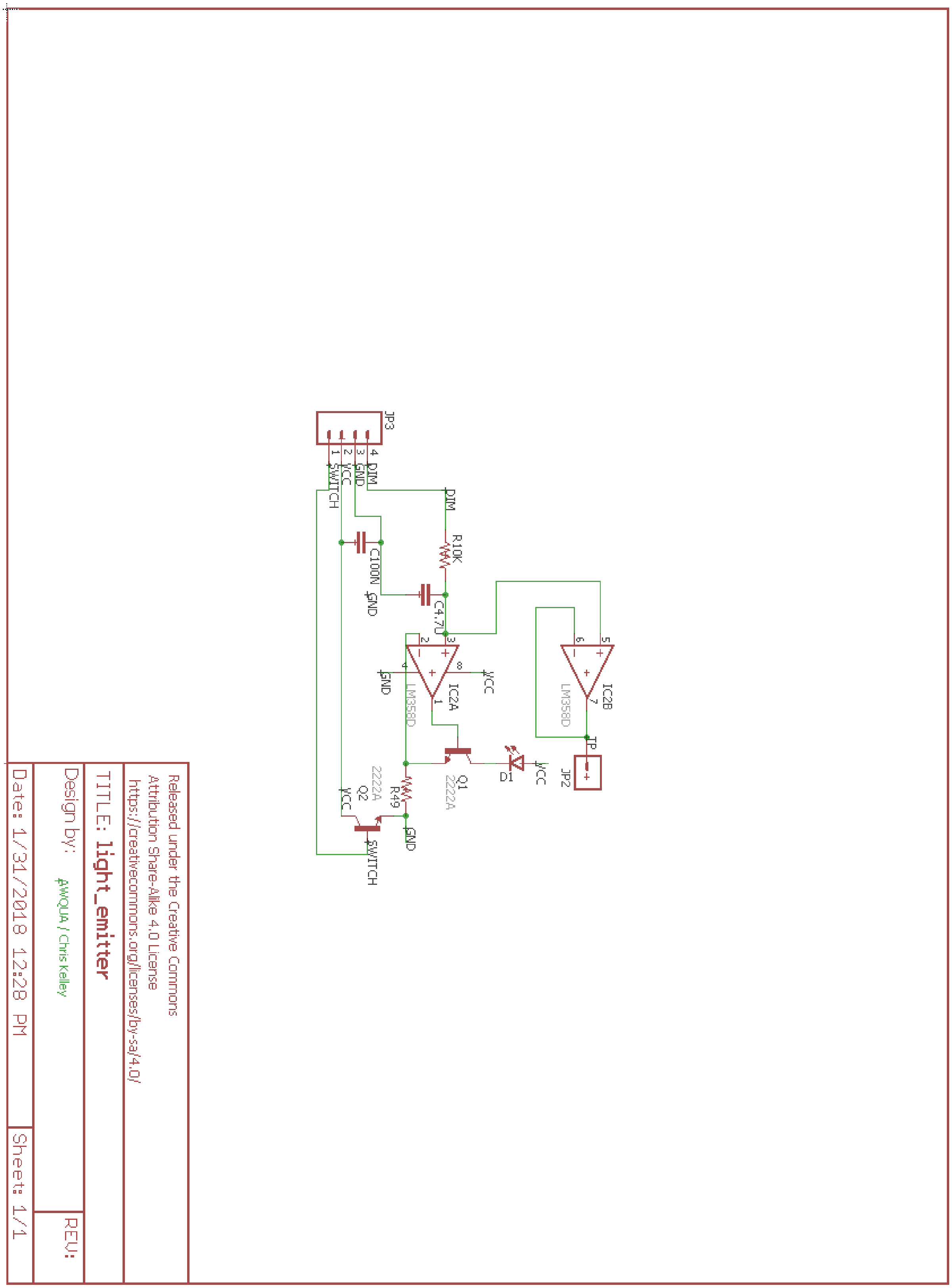
GRN

(a)


JP3
4 DIM
3 GND
2 VCC
1 SWITCH
DIM
R10K
C100N
GND
C4.7U
3
2
8
4
1
+
-
VCC
GND
IC2A
LM358D
5
6
7
IC2B
LM358D
TP
JP2
Q1
2222A
D1
VCC
R49
Q2
2222A
VCC
GND
SWITCH
Released under the Creative Commons
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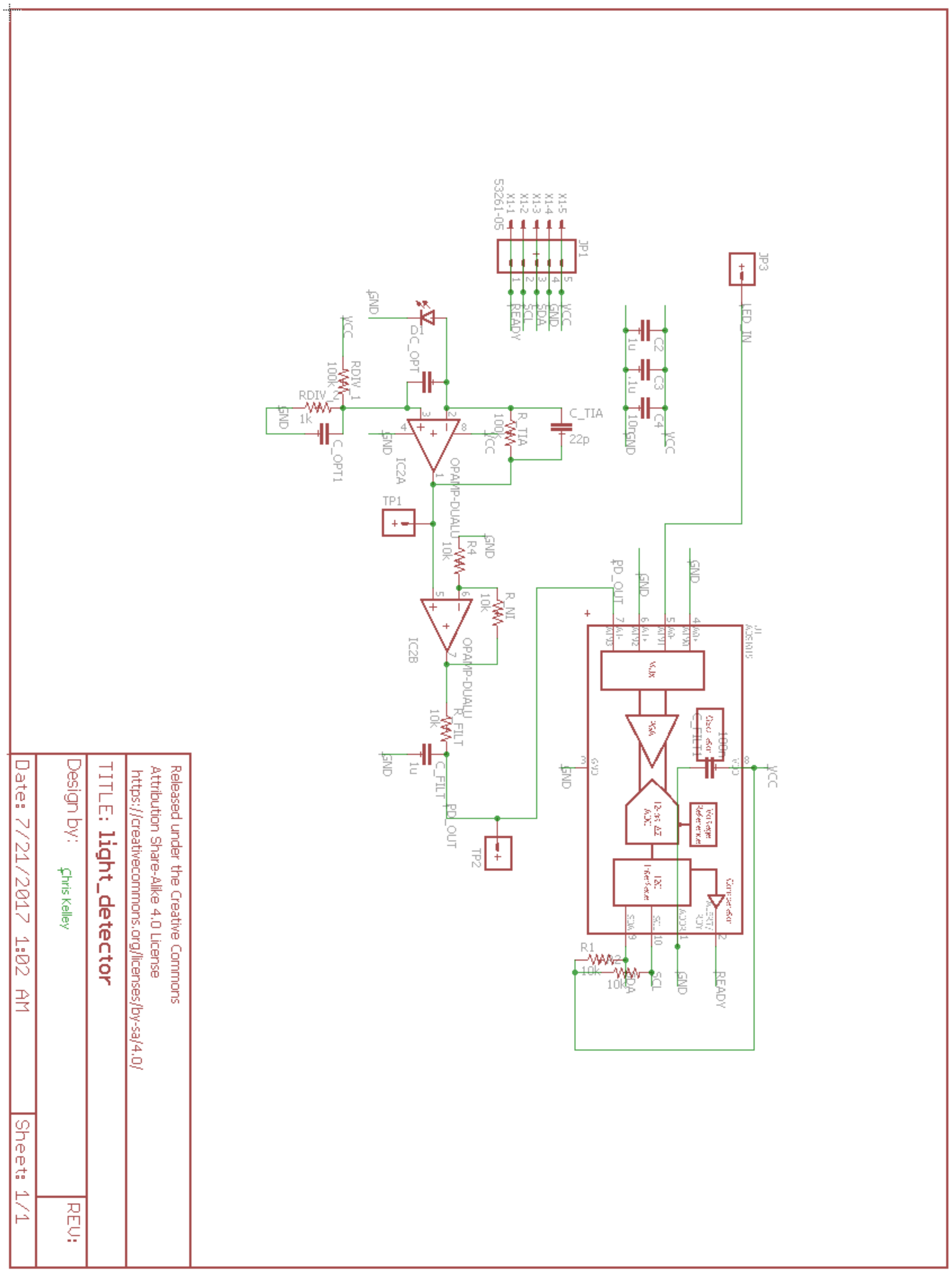
https://creativecommons.org/licenses/by-sa/4.0/
TITLE: light_emitter
Design by: AWQUA / Chris Kelley
REV:
Date: 1/31/2018 12:28 PM
Sheet: 1/1

(b)



(c)

Figure 5.2. (a) Main board schematic; (b) light emitter board schematic; (c) light detector board schematic.

User interface: The device has an OLED screen which can display both text and basic images. User input is captured via three momentary-contact buttons arrayed horizontally below the screen. The user can insert a cuvette containing an aqueous sample into the device, and initiate a measurement by pressing the middle button (while the left button toggles the Bluetooth connectivity, and the right button displays the current timestamp, operating voltage, and ambient temperature on the OLED.)

Sensing: The Black Box handheld turbidimeter uses a simple nephelometric sensing setup in accordance with EPA and ISO nephelometry standards (see Figure 2.1a). An LED with an 850nm peak wavelength is employed as the light emitter, driven by a constant-current supply consisting of an approximately analog voltage signal (which is a low-pass filtered pulse train with a controllable duty cycle, buffered by an op amp in a unity-gain configuration) connected to the base of an N-channel transistor which has the LED at its collector and a low-ohm (current-setting) resistor at its emitter. (See Figure 5.2b.) This setup allows the LED's brightness to be tuned very precisely via the linear adjustment of current to allow for, e.g., ambient temperature compensation.

A wavelength-matched infrared-sensitive photodiode is employed. The photodiode is connected in photovoltaic mode to the inverting input of a transimpedance amplifier employing a high precision (+/-0.1%) feedback resistor with low temperature coefficient (10ppm/C). A resistor divider is used to bias the non-inverting input of the transimpedance amplifier by 1/101 of the operating voltage, to prevent saturation at the ground rail. The output signal of the transimpedance amplifier is amplified two-fold through a second op amp in a non-inverting gain configuration, the output signal of which is low-pass filtered (to reduce any high-frequency electromagnetic interference picked up by the transimpedance amplifier) and fed into a 16-bit analog-to-digital converter (ADC; see Figure 5.2c.). The digitized voltage level is then communicated to the microprocessor for statistical processing and interpolation against the best-fit line (or lines) of a turbidity calibration curve relating the arbitrary ADC units to NTU.

At present, the device does not meet AWQUA and ISO requirements for beam convergence/divergence. This will be addressed in future prototypes by placing small, polished lengths of poly(methyl methacrylate) (PMMA) optical fiber between the cuvette chamber and, respectively, the light emitter and light detector (or, if necessary, by using small glass or plastic lenses).

Interferences: As noted in the draft AWQUA basic turbidity standard, temperature and voltage fluctuations are possible interferences for turbidity measurement (see Section 3.3). The device employs a high-precision (+/-0.3C) temperature sensor for ambient temperature measurements, and measures its own operating voltage through a resistor-based voltage divider (using 0.5% accuracy resistors with low temperature coefficients). Voltage is kept within +/- 0.5% across the recommended operating temperature range of 5C-45C by a high-precision voltage regulator.

Because LEDs can self-heat through usage, ambient temperature measurement is not always sufficient to gauge LED brightness variation due to temperature difference at the diode junction (Johnson 2003). The next instance of this prototype design will therefore include a method for direct sensing of the LED diode junction temperature, such as a two-point measurement of the LED forward voltage for a known gate voltage of the driving transistor.

Memory: The device uses two external EEPROM chips to provide 64KB (or optionally up to 256KB) of low-power, onboard non-volatile memory. This is easily sufficient to store upwards of 1000 time-stamped readings.

Data: The device primarily measures and stores data pertaining to the turbidity of water samples upon request from the user, as well as the operating voltage, ambient temperature, and time and date from the device’s always-on external clock.

The device is not yet fully compliant with the *Reporting* requirements of the draft AWQUA basic turbidity standard (Section 3.3.2) pertaining to batch readings of turbidity levels: it does not yet calculate histograms, although it does calculate mean and standard deviation of a batch of readings, warn the user if a large number of outliers are present in the dataset, and calculate adjusted mean and standard deviation after trimming such outliers.

Communication: In accordance with the draft AWQUA basic turbidity standard, the Black Box handheld turbidimeter has wireless communication capabilities. Bluetooth is included with the device by default, and the device has a two-way serial port that can accept a GSM (2G cell service) modem, a GSM/GPS combination modem (for the additional ability to record the geographical coordinates of a reading), or a wifi service unit. All measurements are time-stamped and relayed upon user request.

At the time of this writing, test data suggest that the Black Box handheld turbidimeter has inadequate voltage regulation when Bluetooth communication is turned on. This appears to be due to the current draw of the Bluetooth unit's status LED. An attempt will be made to resolve this issue by adding a large decoupling capacitor near the ground and power traces of the Bluetooth unit's connector.

5.7.2 Assessment procedure and performance data

The Black Box handheld turbidimeter was calibrated according to the draft AWQUA basic turbidity standard. Calibration option 2 was elected: measuring a series of suspensions of hydrophilic cutting oil in deionized water with both the uncalibrated open-source turbidimeter and a calibrated commercial handheld turbidimeter (the latter a MicroTPI by HF Scientific [Fort Meyers, FL, USA]). A 9-point calibration curve was conducted before the prototype was sent for field testing in Honduras. Results of the calibration are given in Figure 5.3.

While the calibration seems promising, much more testing data are required to evaluate the prototype device. At the time of writing the field testing partners in Honduras have yet to complete basic device testing or offer feedback on the user experience. This will be remedied with continued reminders to complete testing (and, if necessary, the establishment of a separate testing agreement with another field-testing partner).

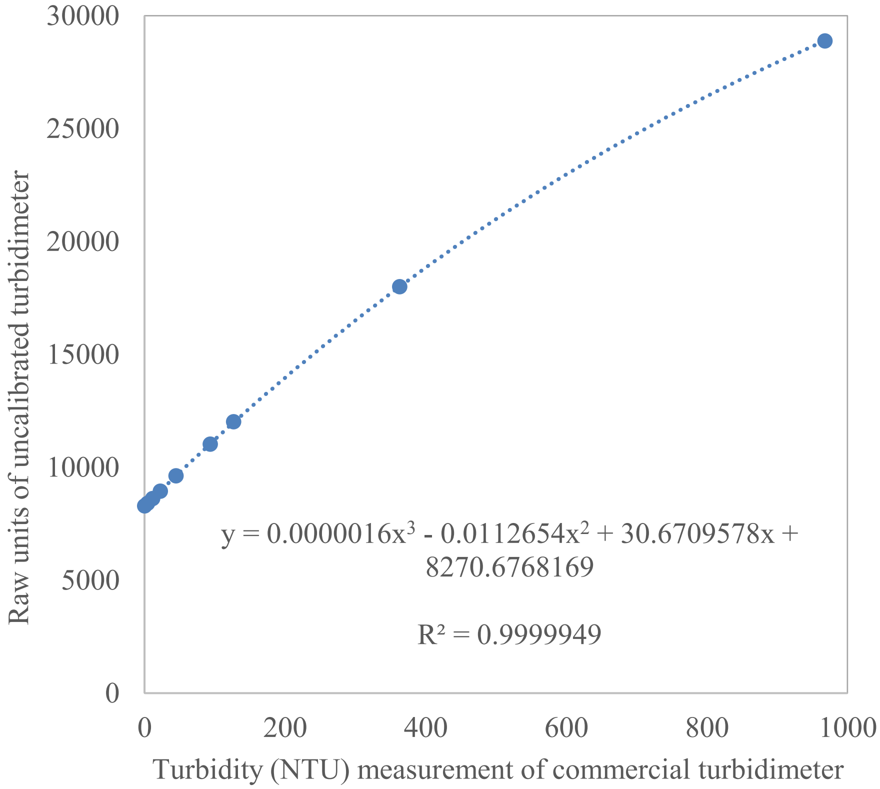


Figure 5.3. Calibration curve (single cubic polynomial best-fit line) of the Black Box handheld turbidimeter against a calibrated commercial turbidimeter.

5.7.3 Acknowledgments

This project was supported financially through an NSF IGERT grant (DGE-1069213), and an EPA P3 grant (OSP# 69442/A001).

5.7.4 Developer contributions

All hardware and caseware aspects of this device design were developed by Chris Kelley. Portions of the firmware were taken from the Affordable Open-Source Turbidimeter (Kelley et al. 2014, and addressed in Chapter 4); contributions to that device are detailed in Section 4.5.5. The hardware, while developed from scratch, is heavily influenced by that of the Affordable Open-Source Turbidimeter.

5.7.5 Supplementary materials for the Black Box handheld turbidimeter

Supplementary materials, including Bill of Materials (BOM) and schematic and layout diagrams for the circuit boards, may be found in Appendix A.

5.8 AWQUA Framework Review of Black Box handheld turbidimeter

User:

Proposed

(U1) A description of the population of end users envisioned (e.g. "rural communities in developing countries").

> This is superseded by (U2).

Prototype – Phase I

(U2) Any new or revised information about the envisioned end-user population description from (U1).

> The Black Box handheld turbidimeter is designed to address water quality monitoring needs in developing countries, in urban and rural contexts, and is intended to be suitable for technicians in water treatment plants as well as non-technical audiences.

Prototype – Phase II

(U3) A conservative estimate of how frequently calibrations should be performed, based on available information on the measurement mechanism and the testing data for the specific device.

> Since only basic estimates of measurement drift have been conducted on this device, calibrations should at present be conducted daily. However, given the fairly rigid structural elements of the device and the well-known measurement mechanism, it seems reasonable

that a more developed version of this prototype could hold calibrations for 1-6 months at a time.

Sampling:

Proposed

(S1) A summary of any known sampling issues which may affect the measurement process or the operation of the Proposed device.

This is superseded by (S2).

Prototype – Phase I

(S2) Any new or revised sampling issues encountered since (S1).

When conducting turbidity measurements, cuvettes must be wiped and dried, both to remove any dirt from the outside of the cuvette and to dry the cuvette and prevent damage to the device's electronics.

Environment:

Proposed

(E1) A description of the intended geographical areas where device use is envisioned.

This is superseded by (E5).

(E2) Existing literature on the applications of the proposed mechanism for measuring the intended parameter.

This is addressed in section 2.1.

(E3) A listing of relevant, currently available commercial monitoring devices.

This is addressed in Section 2.5.

(E4)* An explanation as to why the proposed device should be developed and employed (e.g., rather than an equivalent existing device being employed).

This is addressed in Section 5.6.

Prototype – Phase I

(E5) Any new or revised information for (E1) on the intended geographical areas where device use is envisioned.

The Black Box handheld turbidimeter is intended for general-purpose turbidity monitoring, in field and laboratory conditions. Until the temperature compensation routines for this device are improved, this device is best employed in climate-controlled settings and in tropical field settings that do not experience wide daily temperature variations.

Prototype – Phase II

(E6) A "Cost at Scale" (CAS) BOM with suggested suppliers and hardware costs for manufacturing runs of 1 to 1,000 units in decades.

This is addressed in Table A2.

Device:

Proposed

(D1) A statement of the intended form factor, power source, use setting, data transmission chain, and actuation mode of the proposed device.

This is addressed in Section 5.7 and Appendix A.

(D2) A detailed sketch of the proposed monitoring device should be documented, which provides visual reference to each of the items identified in (D1).

This is superseded by requirements in Prototype stage.

Prototype – Phase I

(D3)* Circuit description, consisting of a schematic, and either a PCB layout (in, e.g., EagleCAD) or breadboard layout (in, e.g., Fritzing).

This is addressed in Figure 5.2.

(D4)* A Logic of Operations description, detailing how the device will interface with a user, and take, calculate, store, display, and transmit measurements.

See https://github.com/AWQUA/improved-handheld-turbidimeter.

(D5)* A diagram of the structural components of the measurement mechanism (e.g. a cuvette chamber or optical window).

This is addressed in Figure A6.

(D6) A Bill of Materials (BOM), detailing the electrical components of the measurement mechanism.

This is addressed in Table A1.

(D7)* Datasheets for key electrical and structural components.

This is available at https://github.com/AWQUA/improved-handheld-turbidimeter.

Prototype – Phase II

(D8) Circuit design files (e.g. EagleCAD BRD/SCH files, as well as CAM files in Gerber RS274-X format).

This is available at https://github.com/AWQUA/improved-handheld-turbidimeter.

(D9) Firmware code in a common language (e.g. Arduino, C, MicroPython, MBED, FreeRTOS).

This is addressed in Section A.2.1.3.

(D10) Software code, if any.

The Black Box handheld turbidimeter uses no software.

(D11) A description of the data storage schema used, if any.

When a turbidity measurement operation is successfully completed, the following data are stored in a record and written to the external non-volatile memory:

1. Number of replicate readings conducted during read event (integer [2 bytes])
2. Unadjusted sample mean and standard deviation of replicates (two floats)
3. Whether ambient light was subtracted from readings via software calculations, or via hardware (Boolean [1 byte], default true)
4. A warning, if more than 10% of replicate readings are beyond two standard deviations from the unadjusted sample mean and the unadjusted sample mean is above 1.0 NTU (Boolean)
5. Whether the sample mean and standard deviation were adjusted by removing outliers beyond two standard deviations from the replicate readings (Boolean)
6. If (5), the adjusted sample mean and standard deviation of replicates (two floats)
7. The operating voltage level of the device (float)
8. The ambient internal temperature of the device (float)
9. The nominal brightness level of the LED, indicated by the duty cycle value of the smoothed pulse train driving the gate voltage of the LED’s constant current source (integer)
10. The timestamp, from the device’s always-on clock, of the beginning of the read event (unsigned long)
11. A newline character to indicate end of record (char [1 byte])

This yields a 37-byte record storage schema.

Additionally, in the microprocessor's onboard non-volatile memory, eleven floating-point variables are reserved for the calibration constants for up to cubic calibration curves, one unsigned long variable is used to store the device's internal identifier number, and two additional unsigned longs are respectively used to store the timestamps of last calibration and last reading taken. When the device is turned on, the timestamp is stored (in seconds since January 1, 1970, as an unsigned long) in a reserved block of the external non-volatile memory.

(D12) A description and link to any firmware or software libraries used to build the device's code.

The Wire library, which abstracts common operations on the two-wire Inter-Interconnected (I2C) bus protocol, is detailed at https://www.arduino.cc/en/Reference/Wire.

The Adafruit ADS1X15 library, which abstracts common operations on the Texas Instruments (Austin, TX, USA) ADS1015 and ADS1115 analog-to-digital converters, is detailed at https://github.com/adafruit/Adafruit_ADS1X15.

The Statistic library, a simple library providing fast and lightweight implementations of common statistical operations, is detailed at https://github.com/RobTillaart/Arduino/blob/master/libraries/Statistic/Statistic.h.

(D13) Design files of internal structural elements, if any, in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD).

This is available at https://github.com/AWQUA/improved-handheld-turbidimeter.

(D14) Design files of internal structural elements, if any, in a common interchange format (e.g. STL, DXF).

This is available at https://github.com/AWQUA/improved-handheld-turbidimeter.

Measurement:

Proposed

(M1) A description of the parameter to be measured, and an explanation of the relevance of this parameter to water quality testing.

This is addressed in Section 2.1.

(M2) A description of the measurement mechanism to be used, as well as other common measurement mechanisms that have been or can be used for the parameter indicated, including a brief comparison of the advantages and disadvantages of the proposed measurement mechanism relative to the other mechanisms listed.

This is addressed in Section 2.1 and Section 4.8.

Prototype – Phase I

No information required.

Prototype – Phase II

(M3) A description of the device calibration procedure and re-calibration procedure (if different).

This is addressed in Section 3.3.3.

X Re-calibration has not yet been conducted for this device (it is a task for the field testing partner that is outstanding at the time of writing).

(M4) A description of the procedure by which calibrations will be verified and the measurement precision and accuracy of the device ascertained. This should include consideration for how to measure drift over time and temperature ranges (and appropriate ranges for any other confounder variable identified in [L3] below).

> This is addressed in Section 3.3.4.
>
> **X** Validation has not yet been conducted for this device (it is a task for both the author and the field testing partner that is outstanding at the time of writing).

Interactive:

Proposed

(I1)* Descriptions of devices at all stages of the AWQUA development framework must be published in a publicly available online repository (e.g. GitHub).

> This is available at https://github.com/AWQUA/improved-handheld-turbidimeter.

Prototype – Phase I

No information required.

Prototype – Phase II

(I2) Following completion of all other requirements in Phase II, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

> The design has been posted in its current state for several weeks at its public Github repository. Feedback on the design has been sought from the Honduran NGO Agua Para El Pueblo (http://www.apphonduras.org), which specializes in rural water treatment and monitoring. Additionally, feedback on the light emitter and detector circuit boards has been sought from a student design team at Appalachian State University (headed by graduate

student Kevin Burgess) – the boards have been incorporated into a low-cost tethered submersible turbidity monitor. Also, Akvo has expressed interest in evaluating an encased version of the prototype.

Legal:

Proposed

(L1) Documentation of primary measurement standards and testing procedures (e.g. EPA, ISO, WHO), if any, for the proposed pair of analyte and measurement mechanism;

> Nephelometry standards are described in EPA Method 180.1 (EPA 1993) and ISO 7027:2016 (ISO 2016).

(L2) A statement acknowledging and crediting all members of the device development team for their contributions.

> This is addressed in Section 5.7.3.

Prototype – Phase I

No information required.

Prototype – Phase II

(L3)* The specific water quality monitoring standard or guideline for which the Prototype device is intended to be a suitable measurement device.

> The draft AWQUA basic turbidity standard is put forward in Chapter 3 as an alternative to ISO 7027:2016 and EPA Method 180.1 standards for open-source turbidimeters; this particular device is in development to meet the draft AWQUA basic turbidity standard.

Quality assurance / quality control:

Proposed

No information required.

Prototype – Phase I

(Q1) Proof of operational measurement utility must be provided in the form of a basic measurement data set, along with a summary of how the device was operated to obtain the data.

> This is superseded by (Q2).

Prototype – Phase II

(Q2) Calibration data, from a calibration procedure conducted according to the water quality monitoring standard selected in (L3).

> This is addressed in Figure 5.3.

(Q3) Validation data, from a validation procedure conducted according to the water quality monitoring standard selected in (L3).

> **X** Validation data have not yet been collected for this device.

(Q4) Drift data, showing the consistency of readings taken with the same Prototype device over time, and across the range of ambient conditions for measurement confounder variables identified in (M4) (or as required by the analyte-specific standard and appropriate for the intended environment of use).

> **X** Drift measurements have only been cursorily performed; over a four-hour period, a measurement variation of less than 0.5% was observed. Ambient light level interference was evaluated with a handheld LED light; with a dedicated black acrylic cover for the top

of the cuvette, measurement variations of less than 0.1% were observed. Ambient temperature interference on measurement was not evaluated at the time of writing.

Construction, Affording, Maintenance, Operation (CAMO) summary:

Proposed:

For the Proposed phase, the CAMO summary should outline what areas of the world – and what measurement niche – the device is intended for use in, and list any foreseen design or manufacturing issues.

The Black Box handheld turbidimeter is intended for worldwide use, in water treatment plants, hospital, schools, vocational training centers, and community water quality monitoring programs. As the device is intended to facilitate regulatory monitoring of turbidity at levels specified in WHO water quality guidelines, it is hoped that a future version of this design can be a useful component of national water quality compliance monitoring programs. The device is not nearly as simple to assemble as the Affordable Open-Source Turbidimeter detailed in Chapter 4, however the device is lightweight, made from relatively common components, and can be assembled in a garage with minimal hardware.

It should be noted that the use of laser cutting may present a manufacturing bottleneck in many LRS contexts; more so than machining or 3D printing. If a laser cutter is not available, the laser-cut acrylic caseware could readily be replaced, with a combination of (1) an optical holder machined from (say) black Delrin, and (2) an 3D-printed external case.

5.9 AWQUA Framework Summary of Black Box handheld turbidimeter

The Black Box handheld turbidimeter is a low-cost analog turbidimeter that which may become useful for general-purpose in field and laboratory. This device was evaluated as a Phase II Prototype. The development team for this device has not yet completed requirements (M3), (M4), (Q3) and (Q4). The device has not met the requirements for a Phase II Prototype, but has met all of the requirements for a Phase I Prototype. Future development effort on this device should focus on water-resistant encasement of the device, improving temperature compensation, and performing validation and long-term use testing.

5.10 References for Chapter 5

Environmental Protection Agency (EPA). (1993). Method 180.1: Determination of Turbidity by Nephelometry; Environmental Monitoring Systems Laboratory Office of Research and Development Cincinnati: Cincinnati, OH, USA.

International Organization for Standardization (ISO). (2016). ISO 7027:2016 Water Quality–Determination of Turbidity.

Johnson, M. (2003). *Photodetection and Measurement: Making Effective Optical Measurements for an Acceptable Cost*. McGraw Hill Professional.

Kelley, C. D., Krolick, A., Brunner, L., Burklund, A., Kahn, D., Ball, W. P., & Weber-Shirk, M. (2014). An affordable open-source turbidimeter. Sensors, 14(4), 7142-7155.

Chapter 6: An AWQUA inline turbidimeter

6.1 Chapter foreword

The purpose of this chapter is to detail an inline open-source turbidimeter and to evaluate this device with respect to the AWQUA device development framework (which covers general and analyte-specific device design and performance guidelines for open-source water quality monitoring devices) detailed in Chapter 3. This evaluation is presented in Section 6.8 in a compact, modular, non-narrative fashion – which is the intended format for AWQUA Framework documentation. To meet the expectations of a more traditional dissertation chapter, key points of documentation for the AWQUA Framework are presented in Sections 6.2 through 6.7 in a narrative format (with reference to preceding Sections and Chapters if necessary material has already been detailed elsewhere in this dissertation).

6.2 Introduction to inline turbidity monitoring

Nephelometry as a turbidity monitoring method is frequently employed in handheld electronic turbidimeters and is described in Sections 2.1 and 4.2. Inline turbidimeters – which can continuously monitor a body of water in an automated or semi-automated manner – often use a nephelometry sensing setup, but may instead (or additionally) employ a more acute angle between light emitter and light detector (see Figure 6.1). This turbidity sensing setup is commonly known as "backscatter" measurement (Down & Lehr 2005). Backscatter detection is less sensitive than nephelometry for low-turbidity liquids but has a fairly monotonic response curve for turbidities up to around 4000 NTU, which is a larger monotonic response window than can be achieved with a nephelometric turbidimeter (Sadar 1998).

In contrast with handheld turbidimeters, which typically have essentially lightproof enclosures in which aqueous samples may be analyzed, inline turbidity monitoring often must be conducted amidst high levels of ambient light. One strategy to deal with this ambient light is to "modulate" the light emitted by the inline turbidimeter (blue arrow in Figure 6.1) – that is, to turn the light on and off at a rate that far exceeds the fluctuation of the background light (Johnson 2003). The light received by the turbidimeter's detector (red arrow in Figure 6.1) can then be filtered to remove frequency far below the modulation frequency (which would include the ambient light) and frequencies far above the modulation frequency (which might include, e.g., electromagnetic interference from radio and cellular communications), before being "demodulated" to a constant signal. This is a very common technique for ambient light rejection, employed for example in television remote controls (Horowitz & Hill 1989). However, in many monitoring situations it may be feasible to simply block ambient light to prevent contamination of the measurement process (Johnson 2003, Lawler & Brown 1992, Orwin & Smart 2005).

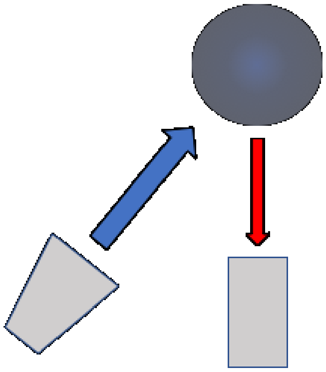


Figure 6.1. Backscatter turbidimeter design. Components: light source (trapezoid), liquid sample (circle), detector (rectangle), transmitted light (large arrow), scattered light (small arrow).

6.3 Existing standards for inline turbidity monitoring

The two key design standards for handheld turbidimeters are EPA Standard Method 180.1 (EPA 1993), promulgated by the US Environmental Protection Agency (EPA), and ISO 7027:2016 (ISO 2016), promulgated by the International Organization for Standardization (ISO). There are currently no specific design standards for backscatter-based inline turbidimeters promulgated by the EPA, ISO, World Health Organization (WHO), or other major national or international bodies with water quality mandates (Down & Lehr 2005). Section 2.4 addresses the relevant details of these standards. A draft turbidity standard designed to facilitate the development of open-source turbidimeters is detailed in Chapter 3.

6.4 Commercial inline turbidimeters

6.4.1 Major manufacturers

A number of major manufacturers produce inline turbidimeters, which typically come in one of two broad categories of form factor: (1) tethered sondes, often employed for long-term immersion in natural water bodies; and (2) high-precision on-line turbidimeters, which pump small volumes of water through a testing apparatus and are frequently employed in water treatment operations. Hach (Loveland, CO, USA) sells the TU5300 on-line low-range laser turbidimeter (2% accuracy for 0-40 NTU, 10% for 40-1000 NTU) with various options for \$2200 to \$2688. HF Scientific (Fort Meyers, CO, USA) sells the MicroTOL series of on-line turbidimeters (2% accuracy for 0-40 NTU and 5% for 40-1000 NTU) with various options for \$1749 to \$2861. YSI (Yellow Springs, OH, USA) sells a turbidity sonde (0.3 NTU or 2% accuracy for 0-999 NTU, 5% accuracy for 1000-4000 NTU) for \$1125 (YSI 2017); this price covers only the probe and tether cable. Hanna Instruments (Woonsocket, RI, USA) offers a multiparameter turbidity sonde (also including pH, electrical conductivity, and dissolved oxygen) with tether cable and handheld datalogger for \$3450 (Hanna Instruments 2017).

6.4.2 Lesser-known brands

Global Water (College Station, TX, USA) sells the TB500 on-line turbidimeter (2% accuracy for 0-40 NTU and 5% for 40-1000 NTU) with various options for \$1823 to \$3060 (Global Water 2017).

6.5 Existing open-source inline turbidimeter designs

Wiranto et al. (2016) produced and evaluated a prototype inline turbidimeter based on a laser diode light source and a TSL250 light-to-voltage sensor (a compact photodiode with integrated amplifier) produced by Texas Instruments (Austin, TX, USA). The laser diode is directly driven rather than being modulated, which can result in self-heating of the diode (Johnson 2003) and incurs the need to physically block ambient light from the measurement apparatus. Their prototype consists of a tethered probe that is immersible, and a base station that is not waterproof. The device was only evaluated over a turbidity range of 0-100 NTU but was evaluated for temporal drift and temperature-induced measurement error over the range of 20C-40C, and exhibited fairly reasonable errors of +/-1% and +/-2%, respectively. While not an open-source design, the publication includes a partial schematic of the device and an unscaled visual layout of the turbidity probe design.

Murphy et al. (2015) detail a novel design for an inline turbidimeter containing both nephelometric and turbidimetric (attenuated light) sensor setups. The €650 sonde is tethered to a base station computer (which costs an additional €150) and was evaluated for turbidity and dissolved water color measurements. The device exhibited reasonable performance over the limited dataset (which does not evaluate ambient temperature interference), though at a price that is perhaps half that of an equivalent commercial device. The paper details a partial schematic and a list of components needed to build the exterior case.

Hu et al. (2014) report on a prototype backscatter-based inline turbidimeter designed for surface water monitoring in China. The device uses an 870nm infrared LED and spectrally matched photodiode in a custom-designed waterproof, pressure-resistant case. The design of the device's detection system is only outlined, but the operating principle is clearly stated as (1) modulation of the light source (with a 2kHz frequency), (2) transimpedance amplification of the light received by the photodiode, (3) bandpass filtering in the range of 0.4kHz – 6kHz, (4) demodulation, and (5) analog-to-digital conversion. Hu et al. present an excellent linear calibration fit for the device over the range of 0-25 NTU (r-squared = 0.9999), making the device potentially well suited for turbidity monitoring at a range relevant to drinking water treatment. It should be noted however that neither temperature interference nor real-world performance was assessed in this paper, and the cost of the device was not specified.

Finally, the open-source science organization Public Lab has released the beginnings of a design for an open-source inline turbidimeter (Public Lab 2017a). Based on the organization's Riffle monitor – a generic form factor featuring a microprocessor, data storage, battery and one or more water quality sensors, enclosed in a reclaimed plastic water bottle (Public Lab 2017b) – the riffle_328-turbidity design is currently available on GitHub as a schematic and an unscaled board layout diagram. The simple design includes microprocessor-modulated light emission via a constant-voltage setup of an LED in series with a resistor, and demodulation of the signal received at a photodiode via a capacitor-resistor high-pass filter in series with a diode-resistor half-wave rectifier and a smoothing capacitor. There seem to be several potential issues with this device, including the lack of a constant-current power supply for the LED (which is needed to provide a linear, rather than exponential, control over LED brightness). As of this writing no performance data for this prototype has been released, and it is worth noting that neither their emitter nor detector is temperature-compensated.

6.6 Why make a new open-source inline turbidimeter design?

There have been fairly few published designs of inline turbidimeters, and particularly where open-source design is concerned. Additionally, while Murphy et al. (2015) detailed a standalone buoy for turbidity monitoring, there were no designs found that are sufficiently compact for untethered monitoring of small surface water bodies such as creeks and streams. Cost, performance, and detail are also suitably motivating factors for developing novel open-source inline turbidimeter design – I would argue that it is inherently useful to have well-detailed and affordable designs for environmental monitoring equipment, provided the designs are suitably performant. It also appears to be the case that no commercial or non-commercial inline turbidimeter design available meets key points of the draft AWQUA basic turbidity standards outlined in Chapter 3.

6.7 The Monocle inline turbidimeter

An inline turbidimeter (see Figure 6.2), intended for inline monitoring in tropical and temperate regions, over a temperature range of 10C – 27C, was developed. It is intended for raw (untreated) water monitoring, and is *not considered suitable* for drinking water monitoring. In accordance with the "Range of detection" language of the draft AWQUA basic turbidity standard (see Section 3.3.2, *Detection* subsection, item [iv]) it should be able to measure turbidity at 5 NTU or below with a bias from the true mean of no more than 10% and a standard deviation of no more than 25%, and measure up to 1000 NTU with a well-characterized and reported bias and standard deviation.

The device is a backscatter turbidimeter that uses 860nm-wavelength LEDs surrounding a photodetector. For simplicity and ease of assembly, and as with the handheld turbidimeter design detailed in Chapter 4, I chose a TSL230RD light-to-frequency sensor (Texas Instruments, Austin, TX, USA). The device has sufficient power to take turbidity measurements every hour for four months, and fits into a convex hull that is 91mm x 57mm x 38mm in size. This monitoring barnacle, or "Monocle", can be built for roughly $60 and is intended for low-cost, low-power, passive monitoring of natural surface water bodies.

Figure 6.2. The Monocle (with visible light filter removed).

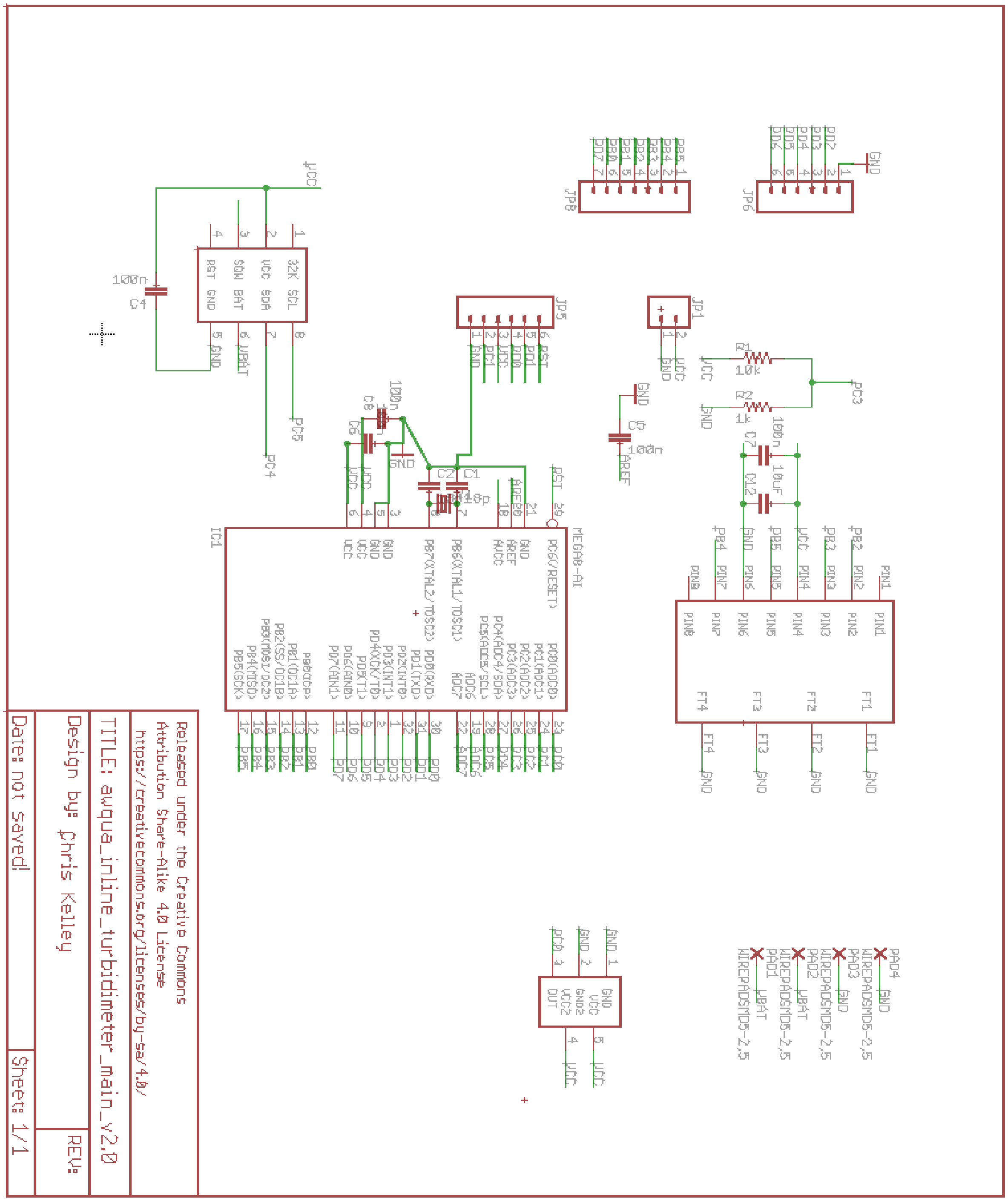
6.7.1 Design Elements

Structure: The Monocle uses a two-part black ABS plastic case and waterproofing gasket manufactured by SERPAC (La Verne, CA, USA). A viewport measuring roughly 25mm x 50mm is cut from the center of the case's top face, over which a larger piece of 2mm-thick clear acrylic sheet is epoxied (see Figure 6.2).

Power: The device is powered by a 3.7V, 2500 milliamp-hour (mAh) lithium-ion battery. Careful selection of components, and judicious use of microprocessor sleep modes were employed to greatly reduce power consumption in between measurements. A dedicated 4.2V charge management chip and an inductive-coupling sub-unit (consisting of a coil of insulated copper wire and a frequency modulation daughter board) allow the lithium-ion battery to be charged wirelessly from a dedicated charging pad (which consists of a matching copper coil and complementary frequency modulation daughter board, a microUSB cable and port, and a 12V DC wall adapter). Schematics of the power management circuit board, sensor board and the main control board, are given in Figure 6.3.

Microprocessor: The device uses an 8-bit, 16MHz microprocessor (ATMega328P) manufactured by Atmel (San Jose, CA, USA), with an external high-precision (+/-20ppm frequency error) oscillator.

Control: The control demands of this device are simple: (1) accept user commands via Bluetooth if the device is currently charging on its charging station; (2) as dictated by the most recently entered operating parameters (see *Commands* below), collect ancillary data (timestamp, operating voltage, ambient temperature), and collect turbidity readings and ambient light readings alternately; (3) transform turbidity readings from raw units to NTU by interpolating against calibration curve, (4) store data in removable memory.


Released under the Creative Commons
Attribution Share-Alike 4.0 License
https://creativecommons.org/licenses/by-sa/4.0/
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Design by: Chris Kelley
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Sheet: 1/1
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JP1
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C5
C6
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C8
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R2
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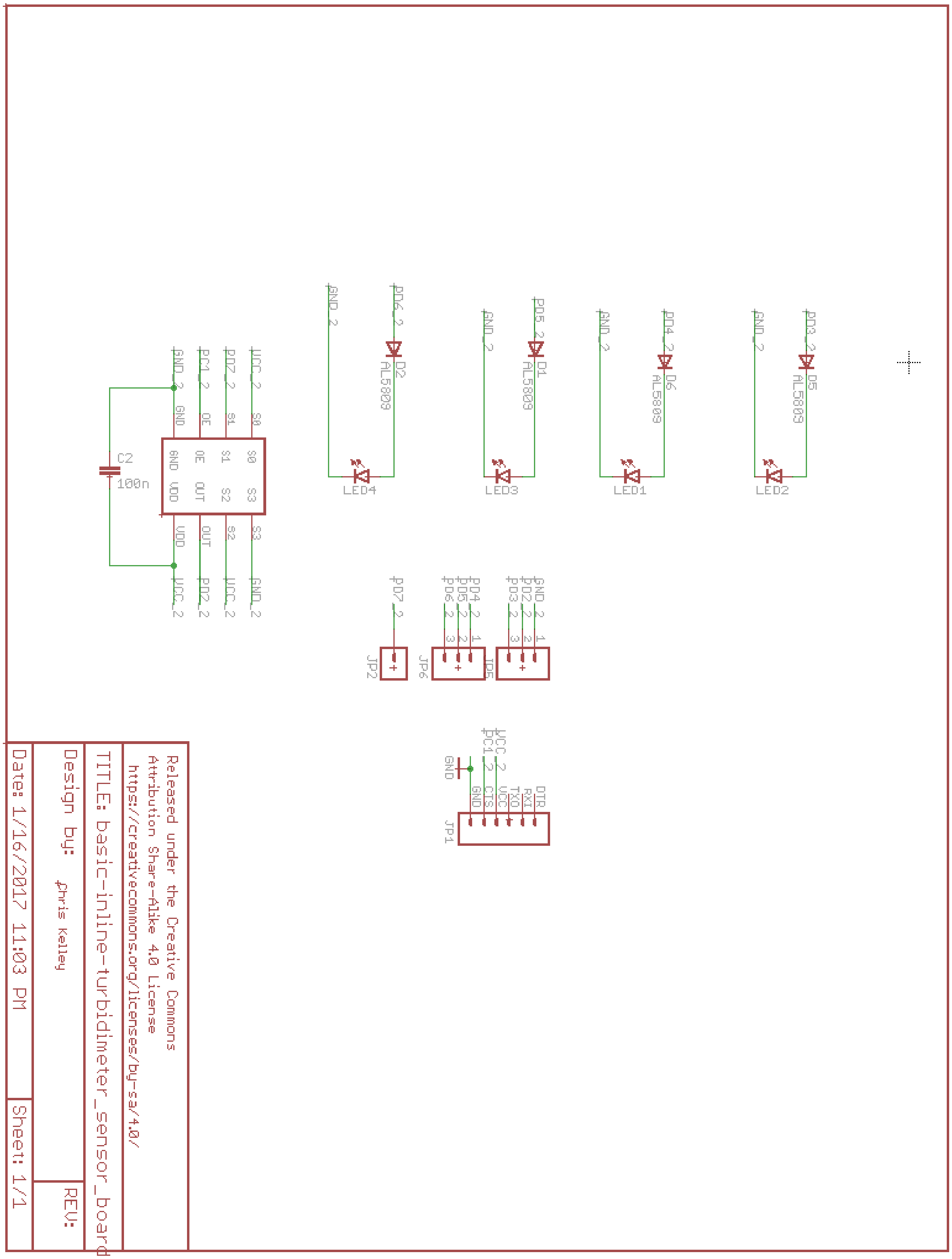
(a)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VCC_2
GND_2
C2
100n
GND_2
PD6_2
D2
AL5809
LED4
GND_2
PD5_2
D1
AL5809
LED3
GND_2
PD4_2
D6
AL5809
LED1
GND_2
PD3_2
D5
AL5809
LED2
PD7_2
JP2
PD4_2
PD5_2
PD6_2
JP6
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PD2_2
PD3_2
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VCC_2
PC1_2
GND
DTR
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TXO
VCC
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GND
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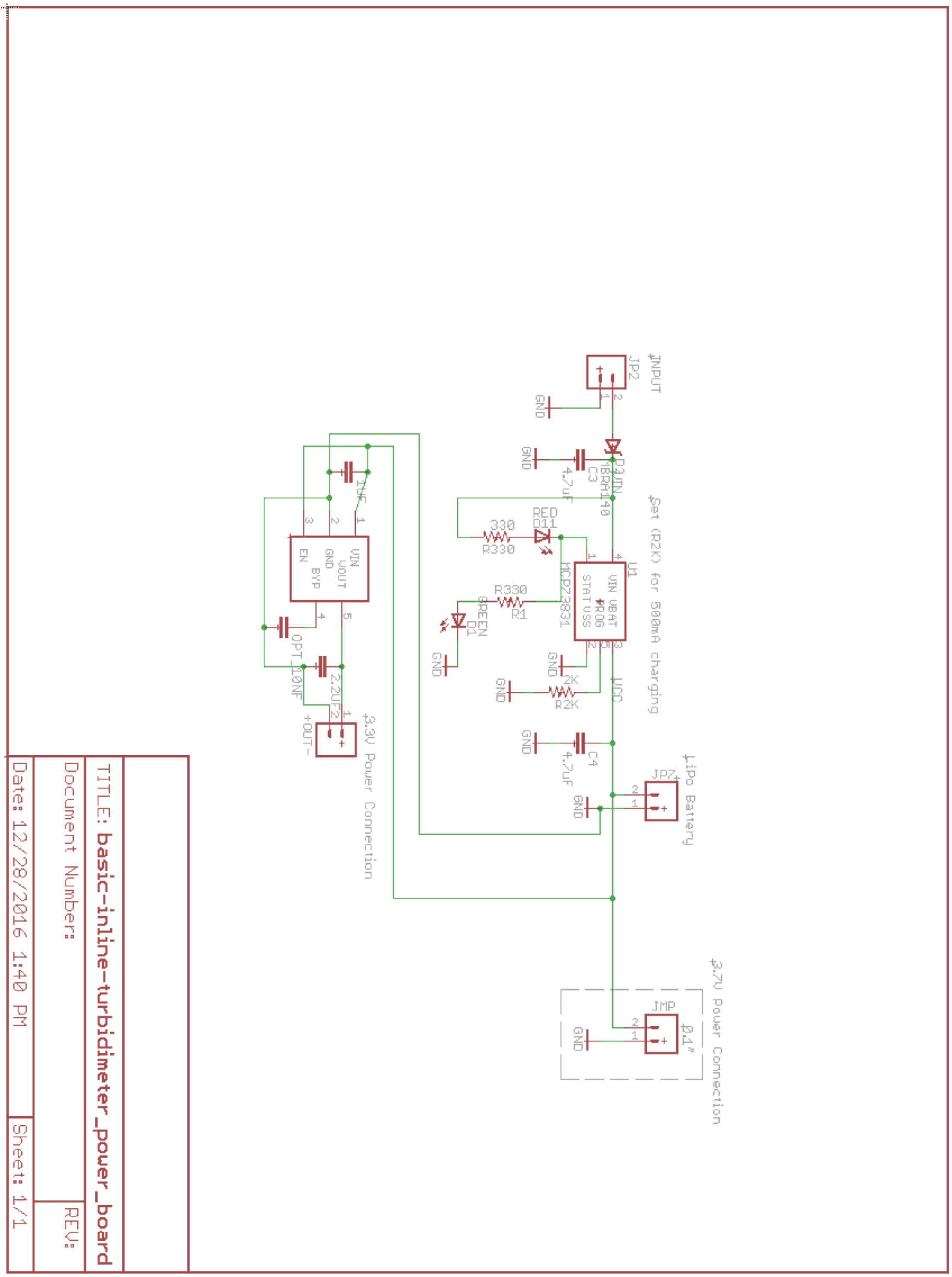
https://creativecommons.org/licenses/by-sa/4.0/
TITLE: basic-inline-turbidimeter_sensor_board
Design by: Chris Kelley
REV:
Date: 1/16/2017 11:03 PM
Sheet: 1/1

(b)



(c)

Figure 6.3. (a) Main board schematic; (b) light emitter / detector board schematic; (c) power management board schematic.

User interface and communication: If the Monocle is turned off or is asleep, the device can be turned on by placing it on the dedicated charging pad. Otherwise the only user interface for the device is via communication over an active Bluetooth connectivity (which is automatically accessible when the device is placed on its charging station). The device's operating parameters can be edited, and the device can be put into sleep mode or recalibrated, via the Bluetooth command interface. The complete command list for the Monocle is given in Appendix B.

Sensing: The light-to-frequency sensor, central to the Monocle's turbidity measurement system, transmits a pulse train to the microprocessor with a frequency that correlates with the intensity of light detected (TAOS 1992). Thus a key design parameter for a light-to-frequency measurement system is the sampling window – a short sampling window has the potential effect of mis-estimating the intensity of detected light (effectively through integer truncation of a continuous variable), while a long sampling window raises the risk of capturing unremovable artifacts due to fluctuations in the background ambient light. Since the light-to-frequency sensor produces an output train with its own tempo, light modulation and demodulation is an incompatible technique for ambient light rejection, and so the design choice was made to limit ambient light influence by physically blocking it through careful placement of the device and by placing a visible-light filter over the detector face. Additionally, software was used to compensate for ambient light through a technique known as "dark count subtraction," which consists of comparing two sequential turbidity measurements. The first reading is taken with the device LED on and the second reading with the LED off; the numerical value of the second reading is then subtracted from that of the first.

The Monocle uses a nominal reading window of 200 to 1000 milliseconds (user adjustable), and takes three to ten replicate readings (user adjustable; default of eight) with dark count subtraction during each measurement event. Read events occur at a scheduled interval of between 30 seconds and two hours (user adjustable). To improve resolution, the device uses a "stretched-window" sampling technique for each read event: the nominal sampling windows of the replicate readings are respectively extended by mutually co-prime fractional times (e.g. 1/4, 1/7, 1/11) and the resulting pulse counts divided by one plus the respective fraction. This is done in an attempt to compensate for the discretization errors that light-to-frequency sensors performs while sensing an effectively continuous process of photon arrival.

For example, if N pulse responses are produced by a light-to-frequency sensor during a static sampling window in ten sampling events, we may deduce with some confidence that the average pulse response rate for the sensor at the detected level of light is somewhere between N and N+1 over the sampling window. That estimate uncertainty is due to the fact that a light-to-frequency sensor can only produce integer multiples of pulse responses. We could refine this estimate by running more replicate readings (in the hopes that some fraction of these readings would register N+1 pulses and some N), or we could extend the sampling window length to reduce the per-read integer truncation error. Using sampling windows of varying lengths, however, breaks up the "rhythm" of performing replicate readings with a fixed sampling window length, and can provide more statistical power than a single reading with a longer sampling window. Given that the purpose of varying the window lengths is, effectively, to maximize syncopation of an ensemble of sampling windows, using mutually co-prime window lengths seems the most appropriate approach (though I have not undertaken to prove the optimality). Testing confirmed that the implementation of this stretched-window sampling technique reduced discretization errors and improved the mean estimate of turbidity readings, compared to replicate readings with fixed window length.

Interferences: As the device uses LEDs as light emitters, the measurements it makes are influenced by ambient temperature variation. The device was simply equipped with a high-precision (+/-0.3C) temperature sensor to detect changes in the device's internal temperature, though a measurement of the LED diode junction temperature (perhaps through calibrated measurement of the forward voltage) would be a more reliable approach as it would account for self-heating of the LED due to usage (Johnson 2003). The expected use environment – a body of water – should generally have small and gradual ambient temperature variations, and the device is designed to automatedly take a continuous series of measurements. Thus, although a basic temperature compensation routine was written into the device's firmware, for testing purposes the device recorded uncompensated turbidity measurements along with the device's internal temperature.

Fouling of the optical path between the light emitter and detector, either through abrasion or (more commonly) biofilm growth, is also a likely interference for long-term immersive turbidity monitoring (Down & Lehr 2005). The device has no active anti-fouling measures (though acrylic was chosen as the viewport material partly because it can be buffed to remove scratches), which may preclude its prolonged use in environment that strongly promote biofilm growth (or barnacle attachment). Field tests over a period of four days conducted by a third party (The Maine office of The Nature Conservancy) did not show any visible signs of fouling after continuous immersion for three days in the Nairobi River.

Memory: Given that the Monocle is intended to record large continuous datasets, adequate on-board memory is crucial. The device contains a 2GB microSD, which can store millions of data points.

Data: At each read event, the device averages the turbidity replicates, and records the timestamp, operating voltage, ambient temperature, and mean and standard deviation of turbidity.

6.7.2 Assessment procedure and performance data

The Monocle inline turbidimeter was calibrated according to the draft AWQUA basic turbidity standard. Calibration option 2 was elected: measuring a series of suspensions of hydrophilic cutting oil in deionized water with both the uncalibrated open-source turbidimeter and a calibrated commercial handheld turbidimeter (the latter a MicroTPI by HF Scientific [Fort Meyers, FL, USA]). A 27-point calibration curve was conducted to characterize an initial prototype, with a linear calibration range for 0-10 NTU and a single quadratic calibration curve for 10-1000 NTU (see Figure 6.4 for the full dataset, and Figure 6.5 for a subset at 0-10 NTU). This would require six sample points for a recalibration. Two additional prototypes were calibrated before being sent for field testing in Kenya. The calibration datasets for these two devices are listed in Table 6.1.

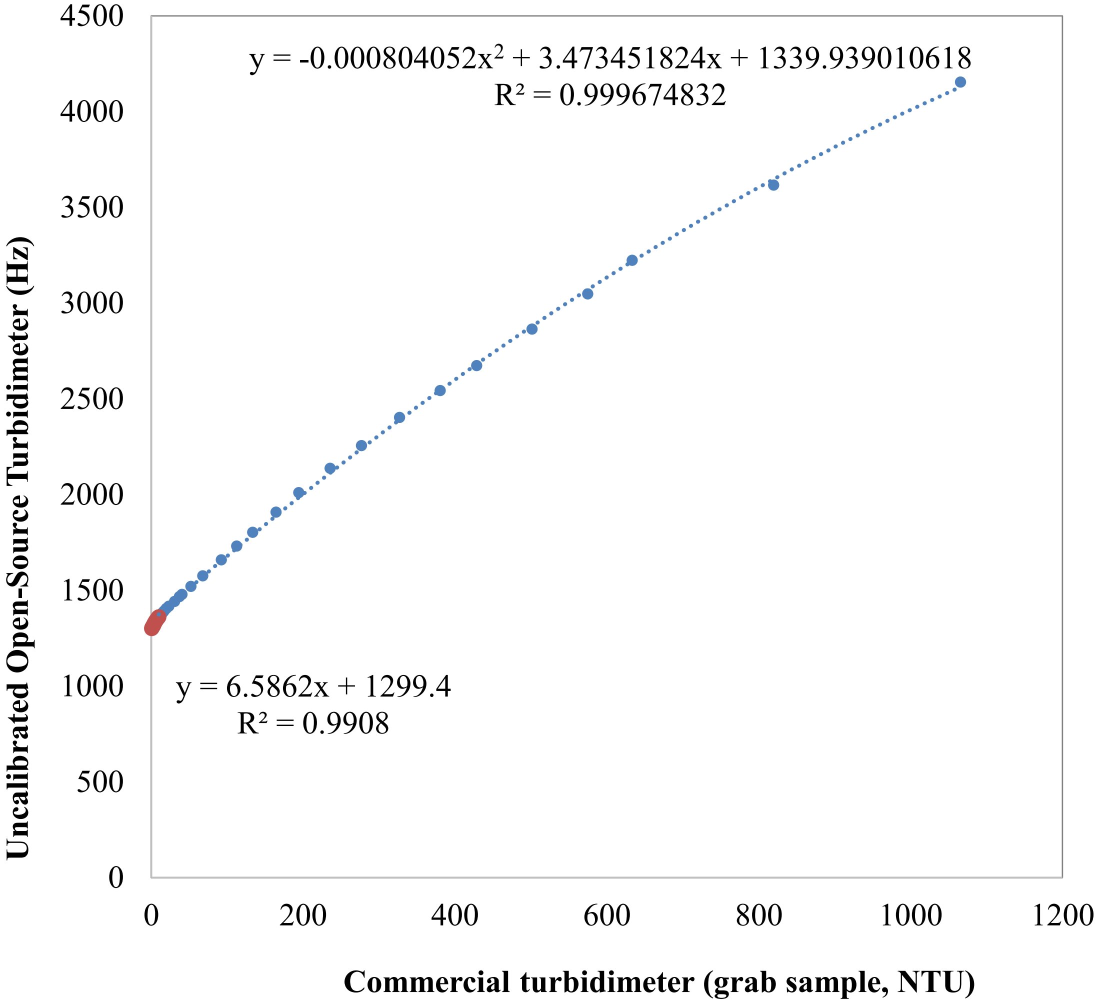


Figure 6.4. A calibration curve for the initial Monocle inline turbidimeter prototype compared to a commercial handheld turbidimeter.

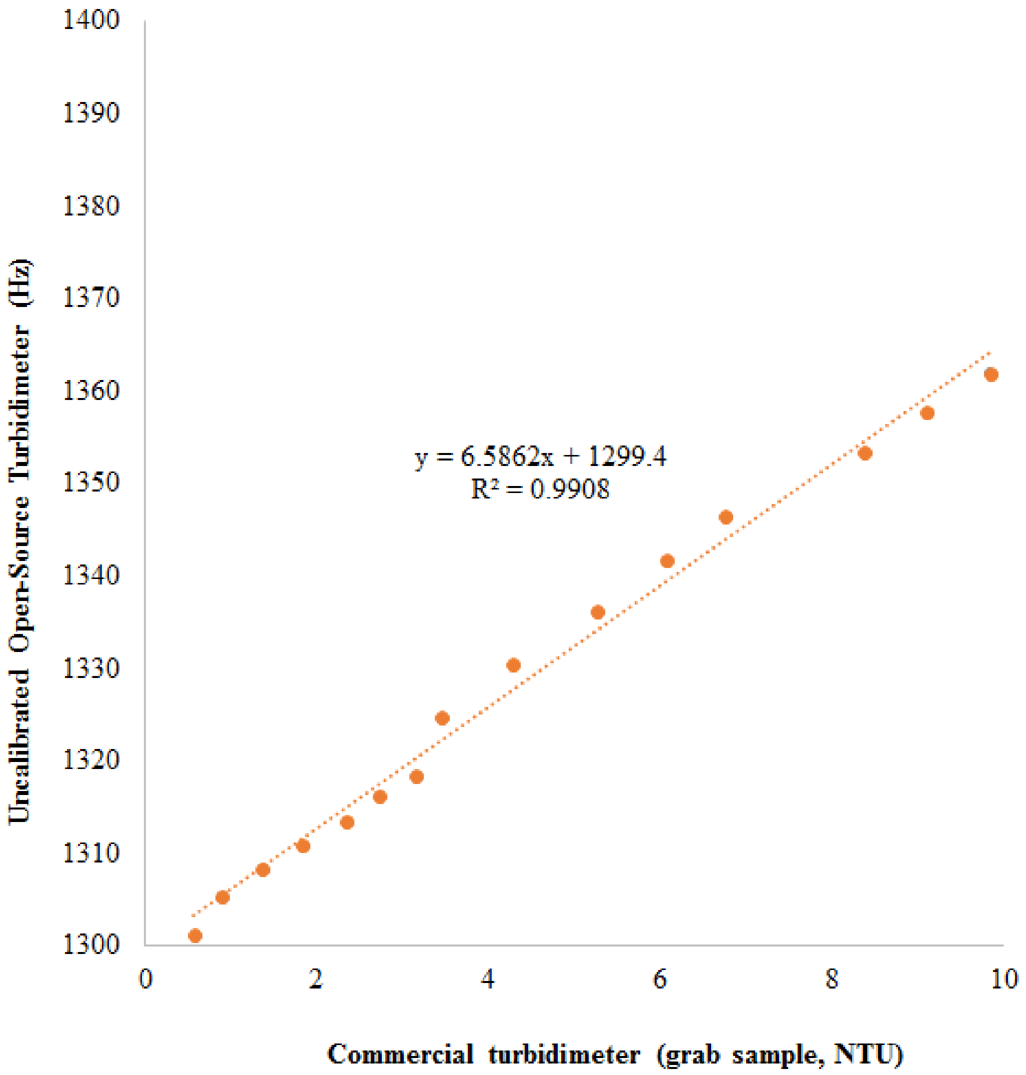


Figure 6.5. Data subset of Figure 6.4 (<10 NTU), with turbidity values under 10 NTU fitted to a linear regression line and turbidity values in the range of 10-1000 NTU fitted with a quadratic regression line.

Despite these promising calibration results, field testing of two Monocle devices in the Sagana River and Thego River in Kenya have made clear the need for a redesign. The testing protocol in Kenya carried out by the field-testing partners (employees of the Maine office of The Nature Conservancy, and Kenyan contacts of theirs) involved placing the two devices in the river for four days of continuous monitoring (readings every ten minutes).

Table 6.1. Calibration data for two prototype Monocle inline turbidimeters (with Monocle readings transformed to NTU for comparison with reference commercial turbidimeter).

Device 1 calibration		**Device 2 calibration**	
Measured	*Reference*	*Measured*	*Reference*
0.62	1.93	0.52	0.4
4.2	3.92	2.5	2.49
7.91	6.99	5.08	5.42
14.41	14.1	10.8	10.57
21.34	21.22	19.41	19.4
35.7	35.68	31.8	31.84
56.65	56.57	47.82	47.5
82.59	83.68	72.75	72.71
119.27	118.36	94.7	94.83
189.93	190.12	123	123.1
282.77	282.73	175.63	175.54
534.5	534.7	272.65	272.67
774.67	775.07	473.65	471.2
951.87	952.52	743.38	744.31
		997.55	997.62

The testing partners have expressed keen interest in a compact, low-cost turbidity monitoring device like the Monocle for spatiotemporally fine-grained measurement of erosion runoff in rivers and creeks (Courtmanche 2016). One of the devices was apparently not put into sleep mode prior to the trip and exhausted most of its battery before testing, and regrettably the DC adapter sent with the inductive recharging station was only rated for 5V instead of 12V, and therefore provided an insufficient rate of recharge. The second Monocle device was successfully tested, however the fluctuation of the ambient background light proved too quick for the programmed sampling window. As a result of rapidly modulating ambient light levels, a circumstance was frequently observed in the dark count subtraction operations where the measured intensity of the ambient light and LED light in the first reading were less than the measured intensity of the (now changed) ambient light in the second reading. Physically impossible results of negative Hertz values! were thus “observed” by the light-to-frequency sensor in the tested Monocle. The device appeared to operate quite reasonably at night, though so few grab samples were collected by the field staff (less than a dozen over the week of testing, between the two rivers) that this is difficult to corroborate.

This device was initially developed to be as electronically simple as could be reasonably arranged, in order to facilitate easy and replicable manufacturing in LRS. Much like the Affordable Open-Source Turbidimeter presented in Chapter 4, on which this device is partly patterned, the Monocle provides a highly affordable monitoring device that may be suitable for some use cases but is not yet a reliable general-purpose turbidimeter. The practical difficulties of handling ambient light rejection purely in software and caseware first came to the forefront during development and testing. It then became apparent through additional testing and research that a more fruitful, and ultimately simpler, development route would be to build a slightly more electronically complex inline turbidimeter that can handle ambient light rejection in hardware operations.

A second version of the Monocle has recently been designed as an attempt to remedy the above-described concerns. The design is modeled somewhat on the analog turbidimeter presented in Chapter 5, however the light emitter is modulated with a 4kHz carrier wave, and the light detector is connected in series with a high-pass filter, full-wave rectifier, and low-pass filter to remove ambient background light and high-frequency electromagnetic interference (see Figure 6.6a). In the spirit of open-source development, this design has been shared with the designer of Public Lab’s turbidity riffle in the hopes that both device designs may benefit from collaboration (Blair 2017).

6.7.3 Acknowledgments

This project was supported financially through an NSF IGERT grant (DGE-1069213), and an EPA P3 grant (OSP# 69442/A001).

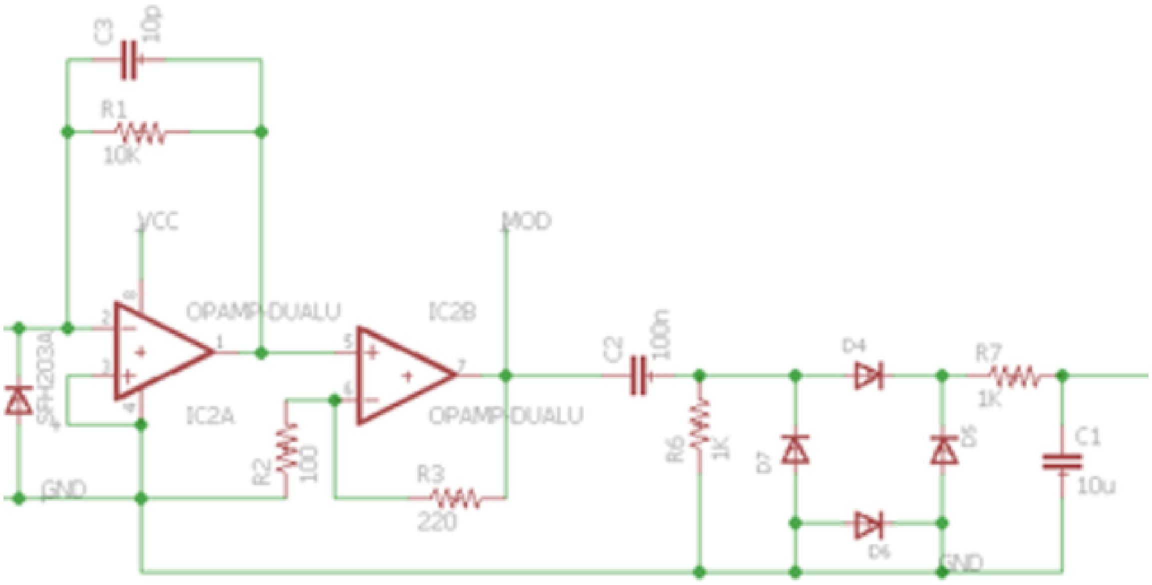


Figure 6.6. A basic demodulation setup for a light-to-voltage based Monocle 2.0, with ambient light rejection handheld by hardware instead of software.

6.7.4 Developer contributions

The hardware, firmware, and caseware of the Monocle were designed by Chris Kelley with the assistance of Johns Hopkins University undergraduate engineering students Vishwesh Majithia and Andrew Backer. Laboratory testing was conducted by Johns Hopkins University undergraduate engineering students Michelle Farhat and Ziwei He, with the oversight and assistance of Chris Kelley.

6.7.5 Supplementary materials for the Monocle inline turbidimeter

Supplementary materials, including Bill of Materials (BOM) and schematic and layout diagrams for the circuit boards, may be found in Appendix B.

6.8 An AWQUA Framework Review of the Monocle inline turbidimeter

The Monocle inline turbidimeter was designed to be a compact, easy-to-use backscatter turbidimeter with inductive recharging and Bluetooth interface which meets AWQUA design guidelines for raw water monitoring. It was in development to reach the Phase III Prototype benchmark before it was redesigned after mixed field-testing results.

User:

Proposed

(U1) A description of the population of end users envisioned (e.g. “rural communities in developing countries”).

> This is superseded by (U2).

Prototype – Phase I

(U2) Any new or revised information about the envisioned end-user population description from (U1).

> The Monocle is designed to be usable by citizens in rural and urban communities concerned with surface water monitoring. Water treatment technicians, development workers, and academics may find the Monocle to be an affordable way to incorporate long-term immersive turbidity monitoring into their professional activities.

Prototype – Phase II

(U3) A conservative estimate of how frequently calibrations should be performed, based on available information on the measurement mechanism and the testing data for the specific device.

> Because insufficient data has been gathered on the Monocle, it is prudent to recalibrate this device before each deployment.

Prototype – Phase III

(U4)* Ease-of-use reports from a tester from a selected and identified range of prototype testers;

> An informal ease-of-use report from Dr. David Courtemanch of The Nature Conservancy is detailed in Section B.3.2. Dr. Courtemanch was the liaison for a field team from The Nature Conservancy who tested two Monocle prototype units in Kenya during the last week of May 2017.

(U5) Hardware assembly instructions;

> These are provided in Section B.1.6.

(U6) Device programming instructions;

> These are provided in Section B.1.3.

(U7) Caseware manufacturing and assembly instructions;

> These are provided in Section B.1.6.

(U8)* Operating instructions, including how to take validation, drift, and recalibration measurements;

> Operating instructions for the Monocle are given in Appendix B (Section B.2) and the sampling protocol is addressed in Section 6.7.

(U9)* Reports of operational issues from at least two weeks of regular use, in conditions that match the use environment identified in (E5) as closely as is feasible.

> **X** Four days of field testing were conducted for two Monocle prototype units, which constitutes only a partial completion of this requirement.

Sampling:

Proposed

(S1) A summary of any known sampling issues which may affect the measurement process or the operation of the Proposed device (e.g. “when conducting turbidity measurements cuvettes must be wiped and dried, both to remove any dirt from the outside of the cuvette and to dry the cuvette and prevent damage to the device electronics”).

> This is superseded by (S2).

Prototype – Phase I

(S2) Any new or revised sampling issues encountered since (S1).

> These are addressed in Section 6.7. Given the testing data for the Monocle, it is recommended that the current version of this device be used only in areas where ambient sunlight can be well blocked through passive environmental means, and that the viewport of the device be cleaned twice per week at minimum,

Prototype – Phase II

No information required.

Prototype – Phase III

(S3)* If the standards specified in (L3) contain sampling requirements, these must be clearly stated in device documentation and followed whenever a requirement at or beyond this stage requires sampling.

> There are no additional sampling requirements stipulated by the standard identified in (L3).

Environment:

Proposed

(E1) A description of the intended geographical areas where device use is envisioned (e.g. "surface water monitoring in tropical areas").

> This is superseded by (E5).

(E2) Existing literature on the applications of the proposed mechanism for measuring the intended parameter;

> This is addressed in Sections 2.1 and 6.1.

(E3) A listing of relevant, currently available commercial monitoring devices;

> This is addressed in Section 6.4.

(E4)* An explanation as to why the proposed device should be developed, rather than a suitable equivalent commercial device being employed.

> This is addressed in Section 6.6.

Prototype – Phase I

(E5) Any new or revised information for (E1) on the intended geographical areas where device use is envisioned.

> The Monocle inline turbidimeter is designed for the third environmental category outlined in the Temperature requirements section of the AWQUA draft turbidity standard: Inline monitoring in tropical or temperate regions (see Section 3.3.2).

Prototype – Phase II

(E6) A "Cost at Scale" (CAS) BOM with suggested suppliers and hardware costs for manufacturing runs of 1 to 1,000 units in decades.

> This is addressed in table B.1.

Prototype – Phase III

(E7) "Bill of Fabrication" (BOF), which outlines the costs of all equipment and services used to produce the Prototype;

This is addressed in Section B.1.7.

(E8) An estimate of the time, and labor, required to produce a Prototype.

To produce one Monocle turbidimeter by hand takes an estimated 75 minutes, as detailed in Section B1.6.

Device:

Proposed

(D1) A statement of the intended form factor, power source, use setting, data transmission chain, and actuation mode of the proposed device;

This is addressed in Section 6.7.

(D2) A detailed sketch of the proposed monitoring device should be documented, which provides visual reference to each of the items identified in (D1).

This is addressed in Figure 6.2 and Appendix B.

Prototype – Phase I

(D3)* Circuit description, consisting of a schematic, and either a PCB layout (in, e.g., EagleCAD) or breadboard layout (in, e.g., Fritzing).

ANSWER

(D4)* A Logic of Operations description, detailing how the device will interface with a user, and take, calculate, store, display, and transmit measurements;

This is addressed in Section 6.7.

(D5)* A diagram of the structural components of the measurement mechanism (e.g. a cuvette chamber or optical window);

This is addressed in Appendix B.

(D6) A Bill of Materials (BOM), detailing the electrical components of the measurement mechanism;

This is addressed in Appendix B.

(D7)* Datasheets for key electrical and structural components.

This is available at https://github.com/iamchriskelley/basic-inline-turbidimeter.

Prototype – Phase II

(D8) Circuit design files (e.g. EagleCAD BRD/SCH files, as well as CAM files in Gerber RS274-X format)

This is addressed in Figure 6.3.

(D9) Firmware code in a common language (e.g. Arduino, C, MicroPython, MBED, FreeRTOS);

This is addressed in Appendix B.

(D10) Software code, if any.

The Monocle inline turbidimeter uses no software.

(D11) A description of the data storage schema used, if any;

This is addressed in Section 6.7.

(D12) A description and link to any firmware or software libraries used to build the device's code;

The JeeLib library, which provides several classes to simplify development on ATMega processors with the Arduino-C language, is detailed at https://jeelabs.org/pub/docs/jeelib/. The Sleepy class of the JeeLib library was used to simplify deep sleep mode toggling in the Monocle.

The SPI library, which facilitates low-level communication with Serial Peripheral Interface (SPI) devices, such as SD cards, is detailed at https://www.arduino.cc/en/Reference/SPI.

The SD library, which provides a high-level interface with SD memory cards, is detailed at https://www.arduino.cc/en/Reference/SD.

The Wire library, which abstracts common operations on the two-wire Inter-Interconnected Bus (I2C) protocol, is detailed at https://www.arduino.cc/en/Reference/Wire.

(D13) Design files of internal structural elements, if any, in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD);

The Monocle inline turbidimeter uses no internal structural elements.

(D14) Design files of internal structural elements, if any, in a common interchange format (e.g. STL, DXF).

See (D13).

Prototype – Phase III

(D15) Case design files in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD);

Unavailable – commercial case. A datasheet is available at http://www.mouser.com/ds/2/364/111-768669.pdf.

(D16) Case design files in a common interchange format (e.g. STL, DXF);

Unavailable – commercial case. A datasheet is available at http://www.mouser.com/ds/2/364/111-768669.pdf.

(D17) Durability summary, including a summary of likely failure points of external and internal structural elements;

The case was drop-tested and lightly stepped upon, neither of which noticeably affected operation or measurements. The key points of potential failure are the rubber gasket and the plastic posts into which fit the screws that secure the two-halves of the case together to make it waterproof.

It should be noted that, with the addition of inductive recharging and Bluetooth communication to allow the case to stay permanently closed, there are many potentially cheaper cases than that currently employed. Two-part acrylic boxes such as those produced by AMAC (Petaluma, CA, USA), properly epoxied shut, are one example.

(D18) A summary of challenges and opportunities in the current Prototype design.

This is addressed in Section 6.6.

Measurement:

Proposed

(M1) A description of the parameter to be measured, and an explanation of the relevance of this parameter to water quality testing;

This is addressed in Section 2.1.

(M2) A description of the measurement mechanism to be used, as well as other common measurement mechanisms that have been or can be used for the parameter indicated, including a brief comparison of the advantages and disadvantages of the proposed measurement mechanism relative to the other mechanisms listed.

This is addressed in Section 2.1 and Section 4.8.

Prototype – Phase I

No information required.

Prototype – Phase II

(M3) A description of the device calibration procedure and re-calibration procedure (if different);

This is addressed in Section 6.6.2.

(M4) A description of the procedure by which calibrations will be verified and the measurement precision and accuracy of the device ascertained. This should include consideration for how to measure drift over time and temperature ranges (and appropriate ranges for any other confounder variable identified in [L3] below).

X Validation of this device has not been sufficiently performed, as field testing after initial calibration suggested the utility of redesigning the sensor system. Temperature is discussed in Section 6.6.

Prototype – Phase III

(M5) If the standards specified in (L3) contain measurement requirements, these must be clearly stated in device documentation and followed whenever a requirement at or beyond this stage requires measurement.

There are no additional measurement requirements stipulated by the standard identified in (L3).

Interactive:

Proposed

(I1)* Descriptions of devices at all stages of the AWQUA development framework must be published in a publicly available online repository (e.g. GitHub).

This is available at https://github.com/iamchriskelley/basic-inline-turbidimeter/tree/master/testing.

Prototype – Phase I

No information required.

Prototype – Phase II

(I2) Following completion of all other requirements of Phase II, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

This design was made publicly available at https://github.com/iamchriskelley/basic-inline-turbidimeter/tree/master/testing.

Prototype – Phase III

(I3) Following completion of all other requirements of Phase III, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

This design has been made publicly available at https://github.com/iamchriskelley/basic-inline-turbidimeter/tree/master/testing. User feedback and independent testing for the first version of this design have been provided by external partners, and feedback on aspects of a second version of this design have been provided by an external party.

(I4) A certification of successful data flow.

Data were successfully recovered via the Monocle's Bluetooth-based user interface by field testing partner David Courtmanche of The Nature Conservancy.

Legal:

Proposed

(L1) Documentation of primary measurement standards and testing procedures (e.g. EPA, ISO, WHO), if any, for the proposed pair of analyte and measurement mechanism;

This is addressed in Section 6.3.

(L2) A statement acknowledging and crediting all members of the device development team for their contributions.

This is addressed in Section 6.7.3.

Prototype – Phase I

No information required.

Prototype – Phase II

(L3)* A selection of the specific water quality monitoring guideline for which the Prototype device is intended to be suitable measurement device;

The draft AWQUA basic turbidity standard – raw water monitoring, in tropic and temperate regions

Prototype – Phase III

No information required.

Quality assurance / quality control:

Proposed

No information required.

Prototype – Phase I

(Q1) Proof of operational measurement utility must be provided in the form of a basic measurement data set, along with a summary of how the device was operated to obtain the data.

This is addressed in Appendix B.

(Q2) Calibration data, from a calibration procedure conducted according to the water quality monitoring standard selected in (L3).

This is superseded by (Q5).

(Q3) Validation data, from a validation procedure conducted according to the water quality monitoring standard selected in (L3).

This is superseded by (Q5).

(Q4) Drift data, showing the consistency of readings taken with the same Prototype device over time, and across the range of ambient conditions for measurement confounder variables identified in (M4) (or as required by the analyte-specific standard and appropriate for the intended environment of use).

Prototype – Phase III

(Q5) Calibration, validation, and drift datasets;

X Calibration data are provided in Section 6.7. Validation and Drift datasets were not collected.

(Q6) Recalibration data, showing the agreement of a calibrated device before and after recalibration;

> **X** Recalibration (and revalidation) were not conducted.

(Q7) A power drain analysis and estimate of use per charge cycle or battery change (if applicable).

> Calculations are based on a resting power consumption of 0.5mA, and hourly measurements: five seconds every hour spent with LEDs on (130mA), and an additional eight seconds taking dark count readings and writing to the SD card (15mA average), assuming 85% discharge from battery, yields 2984 successful turbidity measurements over four months and four days. A one-month battery drain test supported these calculations; further testing has been postponed until the next version of the prototype is ready for testing.

Construction, Affording, Maintenance, Operation (CAMO) summary:

Proposed:

For the Proposed phase, the CAMO summary should outline what areas of the world – and what measurement niche – the device is intended for use in, and list any foreseen design or manufacturing issues.

> The Monocle inline turbidimeter is intended to provide a compact, low-cost solution for long-term immersive surface water monitoring in tropical and temperate regions worldwide. The device has already attracted interest from a leading conservation NGO for erosion runoff monitoring, and could be usefully placed upstream of surface water treatment plants (e.g. to give advanced warning of potential turbidity spikes in water entering the plant for treatment).

Commonly used and widely available electrical and structural components were chosen for the device, and the only power tools needed for assembly are a rotary tool (such as a Dremel) with a sanding disk, an electric skillet for surface-mount soldering, and a soldering iron for through-hole soldering. Altogether these can be purchased in America for under $200, giving the Monocle the lowest overall development costs of the devices outlined in Chapters 4-7.

The proposed changes to the next version of this prototype, principally the use of an analog photodetection setup with modulation and demodulation to perform ambient light rejection through hardware rather than just software, will increase the complexity of the circuit board but should not significantly affect the unit cost of the Monocle.

6.9 AWQUA Framework Summary of Monocle inline turbidimeter

The Monocle inline turbidimeter is a low-cost digital turbidimeter designed for long-term immersive turbidity monitoring. Field testing revealed significant operational issues with the current design of this device. With revision and continued development, the Monocle may become useful for general-purpose field and laboratory monitoring. This device was evaluated as a Phase III Prototype, and the development team for this device has not yet fully completed requirements (U9), (M4), (Q4), (Q5) and (Q6). The device has not met the requirements for a Phase III Prototype, but has met all of the requirements for a Phase I Prototype and is one requirement away from qualifying as a Phase II Prototype. Future development efforts for this device should focus on improving ambient light rejection of the sensor (which might be most robustly achieved by replacing the current sensor with a light-to-voltage sensor), improving temperature compensation, and performing validation and long-term use testing.

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Chapter 7: An AWQUA Jar tester

7.1 Chapter foreword

The purpose of this chapter is to detail a Proposed Design of an open-source jar tester (a device used for analysis of water treatment, among other purposes) and to evaluate this device with respect to the AWQUA device development framework (which covers general and analyte-specific device design and performance guidelines for open-source water quality monitoring devices) detailed in Chapter 3. This evaluation is presented in Section 7.8 in a compact, modular, non-narrative fashion – which is the intended format for AWQUA Framework documentation. To meet the expectations of a more traditional dissertation chapter, key points of documentation for the AWQUA Framework are presented in Sections 7.2 through 7.7 in a narrative format (with reference to preceding Sections and Chapters if necessary material has already been detailed elsewhere in the appropriate narrative form).

7.2 Introduction to jar testing

Jar testing refers generally to the use of a bench-scale testing apparatus (a jar test) to evaluate the impact that chemical and physical processes may have on a larger process scale (e.g. a drinking water treatment plant or a chemical factory) that the jar test apparatus is intended to emulate. Evaluating a potential industrial-scale process – such as the addition of a coagulant to aid in turbidity removal from surface water – on a small sample of water is clearly economically preferable to evaluating that potential process at the scale of the whole treatment plant (provided that the results so obtained are analogous); evaluating gradations of that potential process in parallel reactors allows for simultaneous evaluation which saves time and helps to control experimental confounders. Jar testing is frequently employed to test different dosages of coagulants and coagulant aids at different pH levels for the removal of suspended sediments (and hence turbidity) from water (AWWA 1992). To be effective, a jar tester should contain at minimum (1) two or more transparent mixing vessels, to hold liquid and permit observation and aliquot removal throughout an experiment; (2) an equal number of mixing spindles, one for each vessel, with blades affixed to facilitate mixing of the liquid; (3) a means for setting the rotation of the mixing spindles equally to a desired speed. A typical commercial jar tester is presented in Figure 7.1.

Jar tests have been used in a wide array of coagulation and flocculation experiments, including the removal of turbidity from drinking water (Hudson 1981), the removal of phosphorus from wastewater (Clark & Stephenson 1999), removal of color from landfill leachate (Aziz et al. 2005), treatment of natural organic matter in water (Owen et al. 1995), the use of fly ash for the removal of metals from water (Bayat 2002), removal of dissolved organic nitrogen from surface water (Lee & Westerhoff 2006), and dye removal from industrial wastewater (Chu 2001). Jar testing has also been employed to examine the properties of alternative coagulating agents, derived for example from shellfish (Guibal et al. 2006) and plants (Ndabigengesere et al. 1995, Guzman & Nunez 2015).

Figure 7.1. A typical commercial jar tester. (Source: Phipps & Bird, Richmond, VA, USA.)

7.3 Existing standards for jar testing

Despite the fact that jar tests have been used in water quality monitoring for almost a century (Hudson 1981), neither the EPA nor the ISO provide a standard for jar testing. However, ASTM International – a standards organization whose work often informs EPA standard methods – defines a specification for jar testing in the document ASTM Method D2035-13 "Standard Practice for Coagulation-Flocculation Jar Test of Water" (ASTM 2013). This standard is process-centric: like the EPA and ISO turbidity standards discussed in Chapter 2, it focuses on the procedure of carrying out a test, more than on how test equipment should be designed. Still, the standard does stipulate aspects of three key elements of a jar tester (directly quoted):

> 7.1 *Multiple Stirrer* – A multiposition stirrer with continuous speed variation from about 20 to 150 rpm should be used. The stirring paddles should be of light gage corrosion-resistant material all of the same configuration and size.
>
> 7.2 *Jars (or Beakers)*, all of the same size and shape; 1500-mL Griffin beakers may be used (1000-mL recommended minimum size).
>
> 7.3 *Reagent Racks* – A means of introducing each test solution to all jars [sic] simultaneously. There should be at least one rack for each test solution or suspension. (NB: The intention of this device is permit simultaneous injection of each jar's respective solution.)

ASTM D2035-13 also gives recommends a reagent rack design, consisting of a set of 50 mL test tubes connected at their bases to a plank and spaced apart the width of the stirrer positions. Additionally, it is mentioned that the jars must be transparent and the stirring spindles retractable, to allow undisturbed observation of liquid-filled jars during the test. The shape of the jars is not specified, though it is noted that at least one major manufacturer (Phipps & Bird) sells interchangeable 1L round and 2L square jars. Further, it is recommended that the base of the device, on which the jars sit during testing, contain illumination to aid visual inspection of the jars during testing.

7.4 Commercial jar testers

7.4.1 Major manufacturers

The largest manufacturer of jar testers at the time of writing appears to Phipps & Bird (Richmond, Virginia, USA), a company that sells a variety of other goods ranging from garden furniture parts to military sniper rifle scope accessories. The water quality monitoring titan Hach sells Phipps & Bird jar testers with four or six positions with continuously variable paddle drive speeds (1-300 rpm) which range in price from $2863 to $3609 (Hach 2017). The scientific instrument marketer Cole-Parmer sells a more economical line of ASTM-certified jar testers made by manufacturer Velp Scientifica (Bohemia, NY, USA). At the time of writing Velp jar testers range from a "portable" model (with a handle on top, but still requires access to an AC electricity outlet) with four positions and five selectable drives speeds (20, 40, 50, 100, 120 RPM) for $1476, to a six-position model with continuously varying drive speed (10-300 RPM) for $2721 (Cole Parmer 2017). Additionally, equipment manufacturer and distributor Fisher Scientific sells ASTM-certified jar testers manufactured by Lovibond (Amesbury, UK), with specifications similar to the Phipps & Bird models mentioned above, for $2850 to $3040 (Fisher Scientific 2017).

7.4.2 Lesser-known brands

At the time of writing, some general e-commerce outlets were selling two-position and four-position jar testers from an Indian manufacturer called Indo Sati (for example, SPW Industrial 2017). A company representative confirmed the prices for these two models as $650 and $850, respectively, but did not comment on whether these devices are certified to ASTM (or any other) standards (Indo Sati 2017). Ovan, a Spanish laboratory equipment manufacturing firm, sells two-position and four-position jar testers (neither advertised as ASTM-certified; an inquiry email on this issue received no reply) for $1230 and $1448, respectively (Ovan 2017).

7.5 Existing open-source jar tester designs

No open-source jar tester designs were found. Moreover, there seems to be very little published work discussing the design of jar testers, perhaps because of their conceptual simplicity. Calderon & Gonzalez (2017) detail efforts to fully automate a jar testing process, documenting a setup that includes a commercial inline jar tester, a programmable logic controller, and sensors and actuators. Their setup is performant and impressive, but very expensive (I would estimate their setup to cost more than $10,000 at the time of this writing) and is not an open-source design. Igarashi et al. (1990) evaluated a prototype four-position automated jar tester with turbidimetric (light attenuation-based) sensing at each jar position to detect sedimentation; however the device was only conceptually diagrammed in their manuscript. Satterfield (2005) outlines a brief description, illustration, and set of instructions to build a low-cost, one-position jar tester, however the resulting device is fully manually controlled, provides no mechanism for assessment of the rotational speed of the drive shaft, and uses a potentiometer-based motor drive control mechanism which is inefficient, difficult to use for precise control, and prone to drift [Gottlieb 1994].

7.6 Why make a new open-source jar tester design?

Based on the brief review provided above there appear to be no existing open-source jar tester designs, nor any currently available commercial jar testers that meet reasonable cost and performance requirements for Low-Resource Settings (LRS) application. In this regard, there appear to be a few key challenges and opportunities for employing commercial jar testers in LRS:

Power: All commercial jar testers identified at the time of writing require an AC electrical outlet, which is unavailable or unreliable in many areas of the world.

Analysis: While jar testing – say, of stepped doses of a coagulant for drinking water treatment – can produce visually obvious results, it is often necessary to employ a turbidimeter to compare the residual turbidities in jars after testing. The expense and difficulty of turbidity monitoring in LRS, discussed in Chapter 2, may complicate jar testing in such circumstances.

Communication: The recording of jar test data presents a clerical overhead and chances for human error and dropped transmission of data between stakeholders. Providing for electronic entry of jar testing data – whether via an application on a smartphone, or via an interface built into the jar tester itself – would be prudent.

It would seem that currently the biggest impediment for effective jar testing in LRS treatment plants and laboratories is the cost of commercial devices. There is simply no sensible reason to believe that an adjustable-speed, multi-spindled mixer cannot be reliably manufactured cheaply enough to be sold for a profit at a greatly reduced cost relative to the current commercially available jar testers.

In the next section an open-source, low-cost jar tester is proposed. It is intended to be suitable for general use in LRS communities and is called the "Jar Opener", as a short-hand moniker for an open-source jar tester.

7.7 The Jar Opener

7.7.1 Design Elements

Structure: The Jar Opener will be built on a modified version of the A-frame used by several versions of the popular RepRap open-source 3D printer (see Figure 7.2a). The baseboard could readily be machined from plastic or wood, or 3D printed to incorporate ridges to secure jars in place. This should help keep the device sturdy and relatively light.

Drive: A single motor of suitable torque will be placed at the base of one end of the frame, with gearing to transmit rotation. Dr. Michael Karweit, professor of fluid dynamics at Johns Hopkins

University, has advised that estimating the torque required for mixing multiple water samples of various viscosities and temperatures is a task best approached empirically, with ample overhead built in for margin of error (Karweit 2016). For ample power and ready availability, a 12-24V windshield wiper motor (Figure 7.2b) should be more than adequate.

Figure 7.2. (a) The frame of a RepRap 3D printer (source: reprap.org); (b) a windshield wiper motor (source: Amazon); (c) a beam-break sensor (source: Sharp Microelectronics).

Power: Initial tests suggest that a windshield wiper motor can be driven by as little as 9 volts, so a lead-acid car battery with a simple linear regulator should suffice. It is possible that a lithium-ion battery with a boost converter (to raise the voltage) would be capable of driving the motor, though special control measures might be needed to ensure that current draw (say, in stall situations) doesn't exceed recommended levels for the battery. The power source should be adequate to allow two full jar tests without requiring recharge, for ease of use (and to provide a margin of error to help ensure that at least one full test can be run on an older or halfway-charged battery).

Control: The control demands of this device are simple: (1) accept user commands as supplied, allowing the user to interrupt program flow; (2) adjust drive speed as user demands; (3) monitor and adjust drive speed to match speed target; (4) cut power to motor in the event of error or prolonged stall. A basic 8-bit microcontroller would easily be sufficient.

The motor itself would be powered through Pulse-Width Modulation (PWM – rapidly turning the motor on and off to adjust its speed) rather than direct drive for the sake of precise control and power efficiency (Gottlieb 1994). The ATMega328P from Atmel (San Jose, CA, USA) has a 16MHz clock and independent timer libraries capable of providing a PWM duty cycle with 1024 discrete steps. With proper gearing this motor control setup could provide a resolution of well under 1 RPM over the recommended range of 20-150 RPM.

Active feedback is required to ensure that the jar tester maintains its targeted drive speed. There are several possible mechanisms for this, perhaps the simplest of which would be a rotational encoding wheel – the perimeter of which has several dozen small holes, equally spaced – affixed to the drive shaft and placed in between the arms of a beam-break sensor (see Figure 7.2c). The holes in the encoding wheel briefly and rhythmically permit light to pass between the emitter and detector of the beam break, producing a pulse train from which (with some basic filtering) a rotational speed can be calculated by the microprocessor. To reduce the time necessary to so measure the motor's rotational speed with a given accuracy, the encoding wheel could instead be driven from a secondary drive shaft with a high gearing ratio to multiply its rotational speed.

Gearing: All of the Jar Opener's stirring spindles will be driven at the same speed by the common drive shaft. The gearing ratios must allow operation in the range of 20-150 RPM. Gears could be 3D-printed or cut from plywood, but cast or laser-cut acrylic gears would likely be more enduring. (Machined gears from a less brittle plastic such as PVC or Delrin may be yet more preferable for long-term use.)

Paddles: Hudson and Wagner (1981) detailed a jar tester setup with 2L square jars and a flat-bladed paddle 76 mm in width, though the specific dimensions of the paddles could just as readily be adopted from existing commercial jar testers. Recent work on the impact of jar size and paddle size on turbulence (e.g. Bouyer et al. 2001) might also inform the paddle dimensions.

Jars: Square acrylic jars seem to be advantageous over glass beakers – they are easily fabricated (e.g., laser-cut and chemically cemented), are lighter, cheaper, and are more durable. Additionally, square jars help to prevent rotation of the water body as a whole (relative to round jars) and encourage mixing (AWWA 1992).

Capacity: The Jar Opener will have capacity for five jars.

User interface: The Jar Opener will have a basic LCD or OLED screen which can display both text and basic images. User input will be captured with momentary-contact buttons and a 10-digit keypad.

Communication: The Jar Opener will have wireless communication capabilities – Bluetooth as a default, with GSM (2G cell service) and wifi data connectivity options. The device will be able to accept and display jar test dosing schemes, and accept, store, and transmit manually entered jar rank data (as well as ancillary data including turbidity, temperature, hardness, alkalinity, and pH). All measurements will be time-stamped, and relayed upon user request.

Memory: The Jar Opener will have removable memory (a microSD card).

Sensing: The Jar Opener will have an internal temperature and air pressure sensor. Ambient temperature and pressure data will be appended to stored measurement records by default.

Reagent racks: As mentioned in ASTM D2035-13, reagent racks are used to introduce suspensions to the jars simultaneously. The reagent rack of the Jar Opener will be constructed of a connected row of containers, just like its jars, but with the mouth of each reagent jar narrowed by cementing a cut acrylic lip over each reagent jar to guide the flow of liquid when pouring reagents into the Jar Opener's jars.

External elements: Aqueous suspensions, presumably of a coagulant such as ferric chloride or aluminum sulfate, must be prepared for analysis. This will most likely require: (1) a high-dosage solution of a coagulant, either purchased as a liquid or prepared from water and a coagulant in powdered form; (2) volumetric measuring equipment and clean containers for performing dilutions; (3) safety equipment including dust masks and safety goggles.

7.7.2 Assessment procedure

ASTM Method D2035-13 gives an authoritative procedure for performing a jar test, but that standard is not freely available. The following draft procedure is given as a starting point for operation of a realized version of the Jar Opener, and comparison to a commercial jar tester:

1. Collect in a round plastic container a 10-liter sample of a surface water with high turbidity. Transport this sample to the place of analysis and resuspend any settled sediments by rolling the container back and forth for thirty seconds.

2. Decant 1000mL aliquots of the water sample into each of the Jar Opener’s five beakers, and each of the beakers of a comparable commercial device.

3. Add a “stair-stepped” coagulant dosage (e.g. 0-40 mg/L in 10 mg/L increments) to the beakers of both the commercial and candidate open-source jar tester.

4. Run both the commercial and candidate open-source jar tester for 2 minutes of rapid mix (90 rpm) followed by 30 minutes of gentle mixing (20 rpm) and 30 minutes of settling (0 rpm). Note: this procedure is intended to correspond roughly to the hydraulic retention time of small-scale water treatment plants.

5. For each beaker in each device, rank the relative thickness of the settled coagulant layer and the clarity of the water in the top half of the beaker, and take a turbidity measurement one inch below the water surface. Repeat Steps 1-4 as needed if there is no clear difference between

beakers once the mixing and settling steps are complete.

6. Repeat Step 1-5 two times, using a high turbidity water sample from a different natural body of water each time.

7.7.3 Acknowledgments

This project was supported financially through an NSF IGERT grant (DGE-1069213), and an EPA P3 grant (OSP# 69442/A001).

7.7.4 Developer Contributions

The Jar Opener is covered by the MIT License. Chris Kelley built all components and documentation for the Jar Opener (at the time of writing) and set up the device repository; Johns Hopkins University undergraduate engineering student Andrew Backer tested the current versions of the microcontroller code and drive train to confirm operation.

7.7.5 Supplementary materials for the Jar Opener

Supplementary materials, including suggested circuitry and sample firmware for the microprocessor and motor control mechanism, may be found in Appendix C.

7.8 An AWQUA Framework review of the Jar Opener

The jar tester with integrated data storage and telemetry is currently a Proposed design under AWQUA device development guidelines (detailed in Section 3.2). Documentation requirements of these guidelines at the Proposed stage of development are summarized for this project below.

User:

(U1) A description of the population of end users envisioned (e.g. “rural communities in developing countries”).

> The Jar Opener is intended to be a user-friendly general platform for conducting jar testing experiments in hospitals, laboratories, vocational training centers, and colleges, but was

envisioned specifically to meet the needs of jar testing for coagulant dosage evaluation in water treatment plants in LRS. To this end, the main target audience is water treatment technicians and engineers who cannot readily purchase or maintain commercial jar testers.

Sampling:

Proposed

(S1) A summary of any known sampling issues which may affect the measurement process or the operation of the Proposed device.

To ensure repeatable and meaningful results, the procedure by which aqueous suspensions are prepared must be well documented and strictly followed. For the intended purpose of coagulant dosage testing, this would include adherence to directions from the coagulant manufacturer if available. It would be advisable for any AWQUA jar testing standard to catalog relevant public guidance materials.

Environment:

Proposed

(E1) A description of the intended geographical areas where device use is envisioned.

The Jar Opener is intended primarily for indoor use, and should be suitable for use worldwide.

(E2) Existing literature on the applications of the proposed mechanism for measuring the intended parameter.

Literature is given in Section 7.2, and a relevant standard given in Section 7.3.

(E3) A listing of relevant, currently available commercial monitoring devices.

This is addressed in Section 7.4.

(E4)* An explanation as to why the proposed device should be developed and employed (e.g., rather than an equivalent commercial device being employed).

> Challenges for employing commercial jar testers in low-resource communities are given in Section 7.4.

Device:

(D1) A statement of the intended form factor, power source, use setting, data transmission chain, and actuation mode of the proposed device.

> <u>Form factor</u>: Desktop device, roughly two cubic feet in volume and 5-15 pounds in weight.
>
> <u>Power source</u>: Lead-acid car battery (or potentially lithium-ion battery), or mains electricity with 12V DC power adapter.
>
> <u>Use setting</u>: water treatment plants, hospitals, laboratories, vocational training centers, colleges
>
> <u>Data transmission chain</u>: User input stored in removable (microSD) memory media, and optionally transmitted via (a) Bluetooth to tethered device, (b) SMS to gateway, (c) wifi to server.
>
> <u>Actuation mode</u>: User control through buttons (input) and display (output) with some automated feedback control.

(D2) A detailed sketch of the proposed monitoring device should be documented, which provides visual reference to each of the items identified in (D1).

> This is addressed in Section 7.7 and in Appendix C.

Measurement:

(M1) A description of the parameter to be measured, and an explanation of the relevance of this parameter to water quality testing.

This is addressed in Section 7.2.

(M2) A description of the measurement mechanism to be used, as well as other common measurement mechanisms that have been or can be used for the parameter indicated, including a brief comparison of the advantages and disadvantages of the proposed measurement mechanism relative to the other mechanisms listed.

This measurement mechanism of jar testing is addressed in Section 7.2. One potential alternative to jar testing is the measurement of the zeta potential -- also known as the electrokinetic potential – of a suspension. This measurement of the interparticle repulsion among suspended sediment particles in a solution can help determine how readily a suspension will coagulate and sedimentate (McNaught & Wilkinson 1997, Morfesis 2009). Measurement of zeta potential currently requires highly advanced and expensive machinery (such as the Zetasizer [Malvern 2018]), however, and should not be considered at present a suitable alternative to jar testing in LRS.

Interactive:

(I1)* Descriptions of devices at all stages of the AWQUA development framework must be published in a publicly available online repository (e.g. GitHub).

This is available at https://github.com/AWQUA/open-jar-tester.

Legal:

(L1) Documentation of primary measurement standards and testing procedures (e.g. EPA, ISO, WHO), if any, for the proposed pair of analyte and measurement mechanism;

This is addressed in Sections 7.3 and 7.7.2.

(L2) A statement acknowledging and crediting all members of the device development team for their contributions.

This is addressed in Section 7.7.3.

Quality assurance / quality control:

No information required.

Construction, Affording, Maintenance, Operation (CAMO) summary:

Proposed:

For the Proposed phase, the CAMO summary should outline what areas of the world – and what measurement niche – the device is intended for use in, and list any foreseen design or manufacturing issues.

The Jar Opener is intended for worldwide. Components were chosen for their simplicity, cheapness, and weight. The particular motor form (a windshield wiper motor) was chosen for its widespread availability, the frame was chosen for the widely available parts and existing documentation base, and the microprocessor was chosen for its widespread availability and popularity with small-scale manufacturers of open-source electronics.

It should be noted that the use of laser cutting may present a manufacturing bottleneck in many LRS contexts; more so than machining or 3D printing. Laser-cut components could readily be machined instead if a desktop CNC mill or watchmaker's mill is available; otherwise, 3D printing with replacement as needed could be suitable.

7.9 AWQUA Framework Summary of Jar Opener

The Jar Opener is submitted as a Proposed design for a low-cost, open-source jar testing device with an intended to be appropriate for laboratories, schools, vocational training centers, and above all water treatment plants in LRS communities. The Jar Opener has met all requirements to qualify as an AWQUA Proposed device.

7.10 References for jar tester with integrated data storage and telemetry

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Chapter 8: Summary and recommendations

8.1 Summary of work

The author posits that water quality monitoring in less economically competitive areas of the world is woefully inadequate, and that this results in part because commercially available monitoring devices are generally not designed for such monitoring needs and contexts. To keep the scope of this analysis tractable, turbidity alone has been examined in this work as a limited proxy for broader monitoring of drinking water quality. Currently, ISO 7027:2106 (ISO 2016) and EPA 180.1 (EPA 1993) nephelometry standards are, to the best of my knowledge, the only standards employed for device certification of commercial turbidimeters. In Chapter 2 I have discussed significant shortcomings of employing these standards for regulation of turbidimeter design and explored the potential market impacts of this regulatory arrangement. These discussions led me to posit the need for device-centric turbidimeter certification language. Specific recommendations for such language were raised, centering on: (1) the utility of being able to afford, maintain, operate, and hopefully construct a water quality monitoring device near its locus of use; and (2) consideration of the conceptual model of an end user's monitoring activities.

A two-part Affordable Water Quality Analysis (AWQUA) device development framework has been described in Chapter 3 which addresses the regulatory concerns related to water quality monitoring device design raised in Chapter 2. The first half of this framework provides a general set of guidelines for device development, primarily aimed at open-source water quality monitoring device development and rooted in an analysis of general open-source development guidelines. The second half of this framework provides a structure for articulating parameter-specific standards for the design of open-source water quality monitoring devices compliant with WHO water quality monitoring guidelines. In keeping with Chapter 2, a turbidimeter standard is developed as an example of a parameter-specific standard. This device-centric design standard that attempts to capture and codify key design variables required to produce an electronic turbidimeter that is sufficiently performant for turbidity monitoring as outlined in WHO water quality guidelines.

A turbidimeter development project that largely preceded and informed the framework development process is detailed in Chapter 4. The design had mixed results but is nonetheless reviewed under the AWQUA Framework as a “worked” example. Following this are three examples of water quality monitoring devices under active development by the author, which are presented as additional worked examples of applying the AWQUA device development framework to real water quality monitoring device development efforts. Chapters 5 – 7 detail open-source plans for, respectively, a handheld turbidimeter, an inline turbidimeter, and a jar tester, each of which was developed alongside the AWQUA Framework.

Below are given the author’s take on strengths and limitations of this work, and potential next steps for implementation.

8.2 Strengths and limitations

Strengths

This paper centers on the mismatch between turbidity standards – which are set independently by nations around the globe – and turbidimeter design regulations, which are promulgated by just the EPA and ISO. This appears to be the first paper to identify this situation, and to explore likely consequences of this situation in the commercial turbidimeter market and global turbidity monitoring as a whole.

The analysis of EPA and ISO nephelometry standards presented in Chapter 2 identifies general issues in these regulations such as unaddressed turbidimeter performance variables (variation in ambient temperature and operating voltage) and logical omissions (such as the ISO standard containing no schedule or determination criteria for how frequently to recalibrate turbidimeters). Additional issues relating to the use of these regulations for turbidimeters suitable for turbidity monitoring compliant with turbidity targets of the WHO and many developing nations are identified, such as: (1) the degree of reliance on the primary turbidity standard formazin, which is ill-suited for use outside of well-equipped laboratories; and (2) an issue of accuracy and precision requirements, where the EPA standards are so exacting as to be overpowered for WHO-compliant monitoring, while the ISO standards do not actually set any specific accuracy or precision requirements. To the author's knowledge, this is the first paper to address any of these issues.

The device design framework outlined in Chapter 3 addresses these issues with existing regulations, specifying a set of supplementary performance requirements for turbidimeters which interface with EPA and (primarily) ISO turbidity regulations, and a device development guidance process that is designed specifically to help standardize and streamline development of open-source turbidimeters. Crucially, the device development guidelines outlined provide documentation requirements which require demonstration of several aspects of device performance, and should function as a self-certification mechanism to demonstrate that the device has met its intended parameter-specific water quality monitoring standard.

The device designs described in these Chapters 4 – 7 are, to the best of the author's knowledge, the most detailed and performant open-source designs in their respective device categories at the time of writing. The device in each chapter is thoroughly evaluated against the AWQUA Framework for its appropriate development stage, illustrating both how the AWQUA Framework may be employed and how these example devices may be improved.

Limitations

The AWQUA Framework follows logically from existing regulations, but it is currently a logical exercise – there is no AWQUA-compliant device in the more advanced Registered or Provisional device design categories, or even and AWQUA-compliant device with a significant and positive record of field testing data. If the framework is adopted by developers – and the paper provides no compelling argument as to when or if this will occur – it will likely need amendments.

The devices outlined in Chapters 4 – 7 were largely the work of the author of this paper. This presents a narrow view of the AWQUA Framework implementation process. Further, an amendment process for the framework has not been developed in consultation with other potential developers which may complicate the uptake and usage of this framework. The inclusion in Appendices A and B of suggested question sets for soliciting feedback from device testing partners was intended to demonstrate a default manner for dealing with this issue. Specifically, if a user of the framework (in this case, a device developer) sees the need for an addition to the AWQUA Framework (a set of solicitation questions, for feedback already required under this framework), they can include the proposed addition in their device documentation and then request that this addition be incorporated in the AWQUA Framework. This request for addition could be handled by "forking" the standard – a common term in software development for making a copy of the main development branch of a set of documents for the purpose of editing – and then submitting a "pull request" – a corresponding term meaning a request for a review of edits in a forked development branch for possible inclusion of edits in the main branch.

This in turn implies an additional potential limitation of the AWQUA Framework in its current form. Without a steering committee to judge pull requests and other calls for edits, the framework may be forked in multiple directions without resolution, diluting its potential strength as a regulatory mechanism. The author's envisioned solution for this issue is two-fold: (1) incorporate an organization which can serve as a steering or advisory committee for the development of the AWQUA Framework, and (2) "shop" this framework, as a regulatory mechanism for device development and deployment in developing countries, to relevant organizations (such as the International Association of Plumbing and Mechanical Officials, or the World Health Organization).

Finally, a key point of the AWQUA Framework is to shift, from the end user to the designer, the burden of proof that a water quality monitoring device meets its regulatory requirements. The framework is written to require copious documentation of the performance of compliant devices, and language is included in the Certification section of the AWQUA basic turbidity standard to forbid implied association with this standard for devices that are not fully compliant with the standard. This is intended to close a sort of casual association loophole with current turbidimetry standards – for example a manufacturer emptily claiming that a device is "designed to meet" a standard, rather than that a device "is certified as conformant to" a standard. As the author is not a lawyer, however, it is unclear whether the language included in the standard (in Section 3.3.6) is sufficient to prevent abuse of this standard as an unverified selling point. This is another way in which the AWQUA Framework needs real-world testing.

8.3 Next steps

8.3.1 Device development

Affordable Open-Source Turbidimeter (Chapter 4)

While the shortcomings of this device for regulatory turbidity monitoring are identified in its AWQUA evaluation (Section 4.6), the device has potential as a low-cost, easy to assemble educational tool. Next development steps for this device would include updating the cuvette holder and adding a 3D-printed external case to the device, and possibly designing a circuit board to provide an alternative to the breadboard base of the current device (for improved circuit function and ease of assembly). It might be worth shaping such a circuit board to attach directly to a popular hobbyist microcontroller platform such as the Arduino (Arduino 2017). When these technical updates are completed, it would be worth approaching an after-school science education program (such as Baltimore Underground Science [BUGS]) for possible inclusion of the device in relevant programs.

Black Box handheld turbidimeter (Chapter 5)

Unlike the Affordable Open-Source Turbidimeter, the Black Box handheld turbidimeter is in active development as a potential solution for regulatory monitoring under the draft AWQUA basic turbidity standard (and potentially under ISO 7027). The device needs validation testing, field testing (the author is currently waiting on data from a testing partner), recalibration and revalidation testing, a more complete dataset detailing measurement drift, and updated estimates of needed recalibration frequency.

Temperature compensation was identified as a crucial issue for open-source turbidimeters, both handheld and inline, due to the ineluctable relationship of LED brightness and LED diode junction temperature. A key next step for the development of the Black Box handheld turbidimeter is the inclusion of temperature monitoring at the LED diode junction, which may be accomplished by proxy through calibrated monitoring of changes to the LED forward voltage (since it is powered by a constant-current supply; see Johnson 2003). The comparison of ambient temperature inside the turbidimeter and LED diode junction temperature at startup could also potentially provide an estimate of the long-term decline of the LED's function, so it would be useful to implement in non-volatile memory a lookup table relating these two temperature measures and timestamp at suitable points (say, at 5C intervals) across the operating temperature range, as encountered during normal usage of a given device.

Finally, with acknowledgement to the designers of the MicroTPI handheld turbidimeter (Fisher Scientific, Fort Meyers, FL, USA), the Black Box would benefit from the addition of a small nub in the side of the cuvette chamber (identified in the MicroTPI during the preparation of Appendix D) to help hold the cuvette snugly in place during measurements.

Monocle inline turbidimeter (Chapter 6)

The Monocle is under active development as an inline turbidity monitoring solution, with active interest from a major potential customer (The Nature Conservancy) who is currently serving as a field testing partner. Field tests of the current version of the Monocle have pointed out the serious issue of relying on a light-to-frequency sensor in an environment with potentially high fluctuation of background light. Even with a visible light filter over the sensor, and a software routine to subtract background light from turbidity readings, the fluctuation of background light in field tests (immersing a Monocle prototype in two rivers in Kenya) proved too strong an influence and corrupted daytime turbidity measurements. An analog, light-to-voltage Photodetection front end for the next version of the Monocle (based in part on the photodetection setup of the Black Box handheld turbidimeter), which will permit a much more robust hardware-based solution for ambient light rejection, is already in lab testing.

Like the Black Box handheld turbidimeter, the new version of the Monocle should incorporate temperature monitoring both of the interior space of the device and of the diode junction temperature of the LED. After the new version of the Monocle has passed through basic bench-top testing, it will need the full complement of calibration, validation, drift, recalibration, revalidation, and field testing data required by the AWQUA Framework.

Jar Opener (Chapter 7)

The Jar Opener is a well-described proposal for an open-source jar tester. It needs construction and then evaluation as an AWQUA Prototype device.

8.3.2 Standards and guidelines development

To address the limitations (identified above) of the AWQUA Framework in its current state, a first priority for further development will be the consultation of academics and practitioners of water quality monitoring. There is an urgent need to “play-test” the framework by encouraging a multitude of developers and projects to utilize it, and a parallel need to better articulate mechanisms to solicit and incorporate useful feedback that such testers would hopefully provide. To this end, the author has, at the time of this writing, recently begun the process of incorporating an organization dedicated to the promotion of the AWQUA Framework as a voluntary instrument for open-source device design and a potential regulatory mechanism to promote the use of water quality monitoring devices that are capable of monitoring water quality at target levels specified by the WHO water quality guidelines (WHO 2017).

The AWQUA device development guide (one half of the framework) is designed to be extensible and parameter-agnostic, and a clear next step for the framework is the development of draft device development standards for water quality monitoring parameters besides turbidity. Additionally, while the AWQUA Framework is currently geared towards regulatory monitoring of public drinking water, it could be useful to explore the application of this framework to other water monitoring paradigms such as industrial process monitoring, personal and home surveillance of water, and monitoring education. Finally, as a logical exploration of the regulation and guidance of open-source monitoring device development, the AWQUA Framework might be productively ported to other monitoring domains such as air quality monitoring.

8.3.3 Intellectual property issues

While the AWQUA Framework is primarily geared to encourage the development of new open-source water quality monitoring devices, it is intended to also help facilitate the “opening” of closed-source devices. There seems to be a need to better articulate, and play-test, how and at what stage to matriculate a formerly closed-source product or effort into the AWQUA Framework. One imagines that this would typically be for finished products, thus at the Provisional or Registered stage, but could be implemented for abandoned research efforts and thus merit a matriculation at the Prototype or Proposed stage.

Further, although this paper mostly takes as given the binary distinction between open-source and closed-source, there is logically a variety of practical intermediate steps between these two opposites. It would be worthwhile to explore how a development effort can transition from closed-source to open-source by design. This could take the form of an "opening schedule", in which progressive steps from closed- to open-source are scheduled – such as revocation of EULA clauses on warranty voiding due to opening a device, permission for non-commercializable derivative products, provision of circuit schematics in graphic form only, provision of firmware code, provision of more complete documentation (board and schematics in native file format, BOM and datasheets), provision of assembly instructions, and eventually even provision of blank or populated circuit boards available for purchase.

Perhaps it would be useful to this end to consider the information embodied in a device development effort as a depreciating asset with value as a public good. This is already addressed to some extent in intellectual property law and accounting (for example in the concept of "intangible asset depreciation"; see Smith & Parr 2000). The AWQUA Framework could incorporate notions of humanitarian accounting of intellectual property, to make estimates of the commercial value for the device developer of keeping a technology closed-source versus the humanitarian value (in economic terms) of making the technology open-source. A waste management parallel might usefully be drawn here – just as governments and organizations are pushing to reframe consumer goods waste as a resource management problem to be addressed both before and after manufacturing, the depreciating value of intellectual property contained in monitoring devices (and many other types of manufactured goods) might be addressed as a resource management issue, so that expired intellectual property is recycled in a timely manner to maximize its possible utility public good.

8.3.4 Implementation opportunities

The AWQUA Framework faces an uphill climb as a potential regulatory mechanism, and even as a guidance tool for open-source device development. There are, however, a number of potential implementation opportunities that could be undertaken (especially by a dedicated AWQUA organization), which collectively could make the framework a powerful mechanism for addressing the global need for affordable, repairable water quality monitoring devices and systems.

Integration with existing policy frameworks: The AWQUA Framework is rooted in EPA and ISO water quality monitoring regulations and targeted to WHO water quality monitoring standards. In its current state the AWQUA Framework could help guide the development of effective monitoring tools, but employing those tools in state-regulate monitoring efforts worldwide will require that states recognize the utility of AWQUA monitoring devices and permit their usage for compliance monitoring. A viable path to such recognition would likely involve a working relationship with the World Health Organization.

Enforcement mechanisms: Section 3.4 summarizes the enforcement mechanisms of the AWQUA Framework. These need "play-testing" by a user community, legal evaluation in some cases, and real-world usage generally, which will likely only happen when devices developed under this framework garner public interest.

Curation and distribution of knowledge: The thorough documentation process required by the AWQUA device development guidelines was developed to make compliant devices – whether closed- or open-source – readily inspectable and testable. Being able to open a device and compare its electronics to published device schematics is a powerful knowledge-gathering tool that can help people keep manufacturers honest. Successful curation and wide distribution of AWQUA-compliant devices, and the AWQUA Framework itself, will however require more than requirements for transparency in device design – it will require a user and developer community willing to participate and design and evaluation of devices, and the production of supporting documentation.

Quality control: There are several distinct stages in the development process under the AWQUA Framework, including Design, Fabrication, Subsystems Assembly, Device Assembly, and Testing. In its current form, the AWQUA Framework essentially "bookends" this development process – addressing Design and Testing. For each of these stages, quality control is an issue that is logically and practically independent of knowledge distribution and curation – for example, confirming that electrical components used in AWQUA devices can be traced to reputable manufacturers, and that assemblers are qualified for the tasks expected of them.

Training and certification of manufacturers: A standard that facilitates globally distributed manufacturing is one thing, a global network of LRS-accessible manufacturers is quite something else. To ensure quality of AWQUA-compliant monitoring devices built by small-scale manufacturers, assembly training will need to be formalized and certification processes will have to be developed. This further entails an organized effort to provide oversight to the training and certification process. An interim solution for manufacturing of AWQUA products might involve centralized assembly of complicated subsystems such as circuit boards, with final assembly of finished subsystems taking place in or closer to LRS markets.

An AWQUA steering committee: To grow and develop the AWQUA Framework, and encourage the development of WHO-compliant water quality monitoring devices, it would be useful (and might be critical) to establish a steering committee. This could take the form of an informal group of "super-users", or an incorporated non-profit organization. In light of the issues and opportunities raised above, such an organization might set itself to the following tasks:

1. Maintain records of international shipping methods and cost estimates for low- and middle-income countries;

2. Keep centralized copies of the parameter outline documents required in the Proposed stage of the device development guidance portion of the AWQUA Framework;
3. Maintain a parts library for commonly used electrical and structural components, or help update existing parts libraries like SnapEDA (SnapEDA 2017);
4. Maintain an interactive measurement methodology guidance document, which cross-references water quality parameters with particular measurement techniques and highlights the benefits and potential pitfalls of employing a particular measurement technique (or a particular sensor or type of sensor) for a given parameter;
5. Evaluate electrical components with similar purposes (e.g. ambient temperature monitors) with respect to cost-at-scale, communications protocols, operating voltage and temperature limits, resolution and accuracy, drift, and suitability for particular measurement methods, so that individual device development teams don’t have to repeat this work;
6. Encourage contact between open-source water quality device development teams and facilitate “manufacturing exchange” cooperation (where different labs agree to serve as independent external manufacturers, as required in the Provisional and Proven stages);
7. Mirror or maintain copies of all AWQUA Framework repositories;
8. Promote AWQUA-compliant device development activities on social media;
9. Develop and share “breakout” boards (minimum complete circuits for experimenting) for interfacing with common components;
10. Manufacture and sell AWQUA-compliant devices at the Provisional and Proven stages, if there is not already a dedicated manufacturer for a given device;
11. Provide advice in the manufacturing scale-up process;
12. Work to develop WHO-compliant water quality monitoring device development guidelines, promulgate these through “official” channels, including under the auspices of the United Nations, WHO, and national government water monitoring agencies;
13. Track market demand estimates for affordable water quality monitoring devices;

14. Develop educational resources for assembling, programming, and using AWQUA-compliant devices, and for analyzing data obtained from these devices;
15. Facilitate creation of novel environmental monitoring devices through the development of gamified and novice-friendly circuit board creation software;
16. Bundle purchases of AWQUA-compliant devices into larger orders to cut costs;
17. Scour publicly available IP for environmental monitoring technology, and publish such IP in a readily accessible manner;
18. Develop reference designs for unit processes incorporating publicly available environmental monitoring IP that are not yet incorporated in AWQUA-compliant device designs;
19. Rank and evaluate AWQUA-compliant and commercial devices with respect to price, performance, and user rating;
20. Solicit advice from academics and practicing engineers and scientists to improve AWQUA standards;
21. Organize design contests (e.g. "Hackathons") at the high school or undergraduate level to encourage public involvement in AWQUA device development activities, and to improve the utility of device designs.

References for Chapter 8

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Appendices

Appendix A. Supplementary information for Chapters 4 and 5

A.1 Supplementary information for the Affordable Open-Source Turbidimeter

A.1.1 Design

A.1.1.2 Electronic schematics and wiring

The microprocessor and connected components of the open-source turbidimeter are depicted below in Fritzing (Figure A1) and EAGLE formats (Figure A2). Figure A1 depicts what the device looks like internally, while Figure A2 is a more formal schematic.

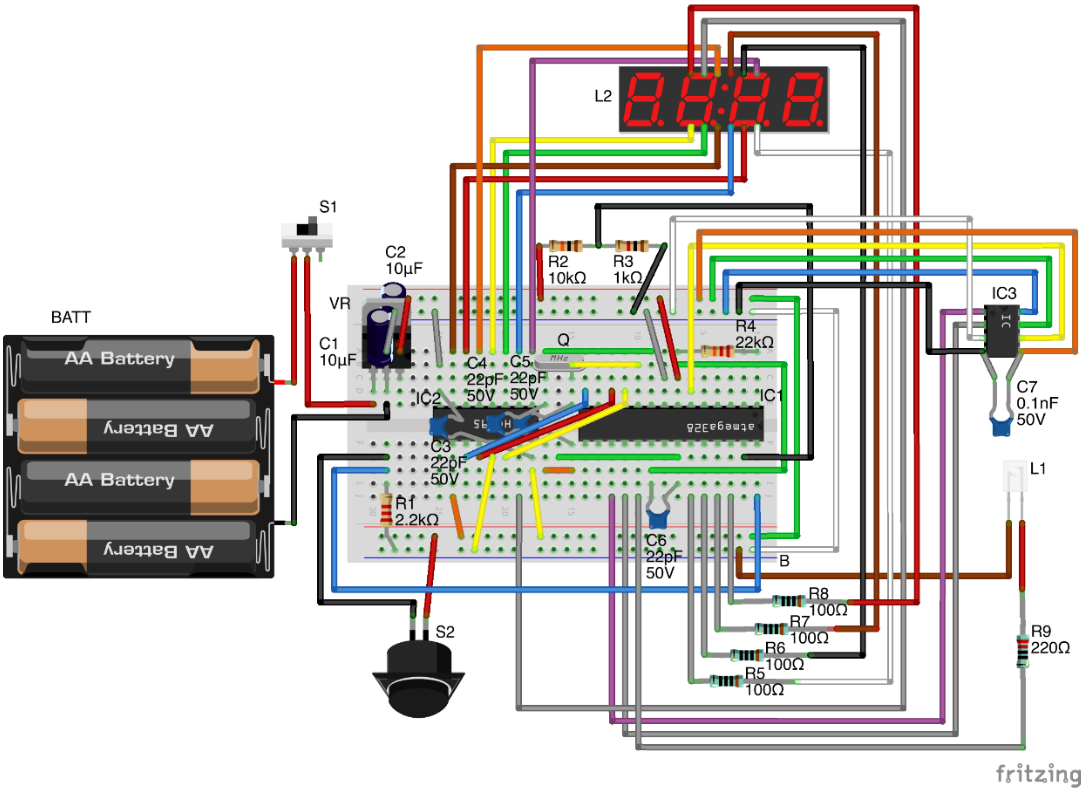

Figure A.1. Depiction of the internal components of the open-source turbidimeter (components labels cross-referenced in Table A1 and Figure A1).

Table A.1. Bill of materials for Basic Handheld Turbidimeter, showing component cost and aggregate price per unit at orders of magnitude.

			Price at Quantity ($)		
Qty	**Description**	**Vendor**	*1*	*10*	*100*
1	Power Switch	Electrodragon	1.6	0.32	0.32
1	860nm Infrared LED	Mouser	1.12	0.722	0.64
4	1/4 Watt 100 Ohm Resistor	Mouser	0.12	0.08	0.032
2	10uF Capacitor	Mouser	0.32	0.219	0.099
1	595 Shift Register	Mouser	0.57	0.477	0.29
1	5V Voltage Regulator	Mouser	0.61	0.511	0.312
1	TSL230RD Sensor	Mouser	3.87	3.46	2.84
1	16MHz 18pF Crystal	Mouser	0.48	0.433	0.3
1	8-bit Microcontroller	Mouser	2.14	2.14	1.78
4	22pF Capacitor	Mouser	0.15	0.15	0.117
1	0.1nF Capacitor	Mouser	0.1	0.1	0.044
1	1/4 Watt 2.2 kOhm Resistor	Mouser	0.12	0.12	0.12
1	1/4 Watt 10 kOhm Resistor	Mouser	0.12	0.12	0.12
1	1/4 Watt 1 kOhm Resistor	Mouser	0.1	0.1	0.1
1	1/4 Watt 22K Ohm Resistor	Mouser	0.1	0.1	0.1
1	1/4 Watt 220 Ohm Resistor	Mouser	0.19	0.19	0.19
1	Vectorboard (4 cm x 6 cm)	Electrodragon	0.5	0.5	0.5
1	Black Button	Mouser	1.56	1.56	1.09
1	7-Segment Display	Electrodragon	2.1	2.1	2.1
1	4xAA Battery Holder	Mouser	1.22	1.22	0.904
1	M/F Jumper Wires (22 ct.)	Electrodragon	1.2	1.2	1.2
1	Printed Cuvette Holder**	Octave	0.92	0.92	0.92
1	Printed Case Exterior**	Octave	4.88	4.88	4.88
1	Assembly	self	15	10.5	10.5
1	Calibration	self	11.25	11.25	11.25
		Cost Per Unit ($):	**$40.22**	**$33.03**	**$30.04**

Note: **3D-printed component: price estimate only reflects cost of raw material.

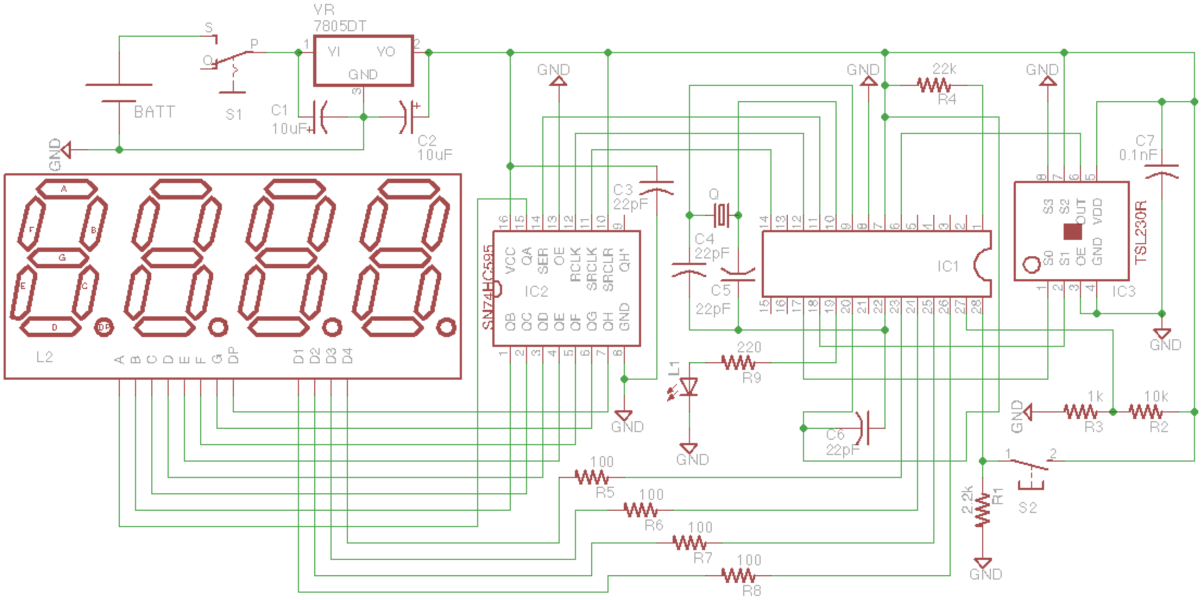

Figure A.2. Schematic of the circuit board for the open-source turbidimeter (components labels cross-referenced in Table A1 and Figure A1).

A.1.1.3 Firmware

```
/*

For a copy of the most up-to-date code, please visit:

https://github.com/wash4all/open-turbidimeter-project


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   MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the

   GNU General Public License for more details.
```

```
   You should have received a copy of the GNU General Public License
   along with this program.  If not, see <http://www.gnu.org/licenses/>.
*/


// Flags
  boolean debug = false;  // IMPORTANT to update EEPROM, change this to true
 boolean using_modem = false; // if not using a GSM modem, change to false


  #define NO_PORTD_PINCHANGES
  #define NO_PORTC_PINCHANGES
  #include <GSM.h>
  #include <PinChangeInt.h>
  #include <EEPROM.h>
  #include <EEPROMAnything.h>


// Definitions
  #define PINNUMBER "1111" // PIN Number for SIM card
  #define VERSION_BYLINE "Open Turb Prj\nBIOS v1.9\n2014-02-11\n"
  #define IR_LED   13    // light source
  #define TSL_S1   12    // S1 and S0 are pins on the TSL230R chip
  #define TSL_S0   11
  #define TSL_FREQ  4    // frequency signal from the sensor
  #define BPIN     A5    // external button
    #define VPIN     A4    // voltage read pin
    #define DIV_R1 10000   // resistance for R1
    #define DIV_R2  1000   // resistance for R2
  #define SAMPLING_WINDOW 1000    // milliseconds between frequency calculations
  #define HIGH_SENSITIVITY  100   // sensitivity settings, set via S0 and S1 pins
```

```
 #define MED_SENSITIVITY   10    // ...
 #define LOW_SENSITIVITY   1     // ...
 #define READ_REPS 6    // number of readings the turbidimeter will take per
                        // button press (average is used for reporting)

// Set up GSM library
 GSM gsmAccess;
 GSM_SMS sms;
 boolean notConnected = true;
 char* remoteNum = "14105555555";
 char* selfNum = "15125555555";
 String sNum = "151255555555";

// Global Vars
 int  scale_divider = 2, sensitivity = HIGH_SENSITIVITY;
   // scale_divider must match hardwired TSL_S2 and TSL_S3 settings,
   // sensitivity sets TSL_S0 and TSL_S1 settings
 int bpress = 1023;
   //variable for digital mapping of analog button press event
 float div_fact = 1;
   //division factor, to normalize sensor output by voltage level
 long freq_jump_hi = 50000, freq_jump_lo = 4000;
   // (These settings could be used to dynamically set sensor sensitivity)
 unsigned long timer, frequency;
 volatile unsigned long pulse_count = 0;
   //interrupt variable; stores count data coming from sensor
 boolean bpressed = false;
 boolean sufficient_battery = true;
```

```
  const int num_displays = 4;
  const int shift_latch = 5;  // RCLK
  const int shift_clock = 8;  // SRCLCK
  const int shift_data = 6;   // SER
    // The above three pins connect the 74HC595 shift register
  const int dispPorts[num_displays] = {A3,A2,A1,A0};
  String language = "english"; //"espanol";

  // Codes the characters: 0-9, '.', '-', blank
  const byte SevenSegNumbers[13] = {B11000000,  B11111001,  B10100100,  B10110000,
                                    B10011001,  B10010010,  B10000010,  B11111000,
                                    B10000000,  B10010000,  B01111111,  B10111111,
                                    B11111111};

  // Characters: rEdYLStO
const byte SevenSegLetters[8] =  {B10101111,  B10000110,  B10100001,  B10010001,
                                    B11000111,  B10010010,  B10000111,  B11000000};

// Use this structure for storing data & retrieving data persistently in EEPROM
  struct config_t{
    int foo;          //example
    long machine_id;   //example
    unsigned long last_calibration_timestamp; // in seconds since 1/1/1970 12:00a
      // define calibration constants for 4 calibration curves
      // y is the lower bound, m is the slope, b is the the y-intercept (y=mx+b)
      // PLEASE NOTE: The calibration curve included in this code has five linear regions instead of four, and
is the
      // result of additional device testing to that reported
```

```
//in the article An Affordable Open-Source Turbidimeter
    float y0, y1, y2, y3, y4,
          m0, m1, m2, m3, m4,
          b0, b1, b2, b3, b4;
  }
  config;

/*--------------------------------FUNCTIONS---------------------------*/
void setup() {
    pinMode(TSL_FREQ, INPUT); // light sensor
    pinMode(TSL_S0, OUTPUT);  // light sensor
    pinMode(TSL_S1, OUTPUT);  // light sensor
    pinMode(IR_LED, OUTPUT);  // light source
    pinMode(BPIN, INPUT); // button
    pinMode(VPIN, INPUT); // voltage
    pinMode(shift_latch, OUTPUT); // shift register
    pinMode(shift_clock, OUTPUT); // shift register
    pinMode(shift_data,  OUTPUT); // shift register
    for(int i = 0; i < num_displays; i++){
      pinMode(dispPorts[i], OUTPUT);
      // set display pins to output
    }

  // Startup procedure
    digitalWrite(IR_LED, LOW);  // light source off
    delay(200);
    turnOffDisplay();
    setSensitivity(sensitivity); // set sensor sensitivity
```

```
  timer = millis();
  displayForInterval(-1, "dashes", 1000);

// Prepare sensors
  if(divisionFactor_TSL230R() < 0){
    sufficient_battery = false;
    displayForInterval(-1, "error", 2000);
  }
  else{
    displayForInterval(-1, "ready", 2000);
    turnOffDisplay();
  }

if(debug){
  config.foo = 255;
     //EEPROMAnything seems to need the struct to start with a integer in [0,255]
  config.machine_id = 11111111; //example
  config.last_calibration_timestamp = 1390936721;
  config.y0 = 0;
  config.m0 = 0.02876;
  config.b0 = -2.224;
  config.y1 = 87.63;
  config.m1 = 0.039;
  config.b1 = -3.124;
  config.y2 = 276.94;
  config.m2 = 0.04688;
  config.b2 = -5.298;
  config.y3 = 2472.3;
```

```
    config.m3 = 0.05223;
    config.b3 = -18.525;
    config.y4 = 6049;
    config.m4 = 0.0721;
    config.b4 = -138.9;
    EEPROM_writeAnything(0, config);
     // Write example calibration settings to EEPROM memory
  }
  else{
    EEPROM_readAnything(0, config);
      // Read calibration data from EEPROM memory
  }
}

void loop() {
  if(sufficient_battery){
    bpress = analogRead(BPIN);
      // check for button press event (0 = pressed)
    if (bpress == 0){
      bpressed = true;
      divisionFactor_TSL230R();
        // read, but discard first reading
      div_fact = divisionFactor_TSL230R();
        // take another reading of voltage divider
      if(div_fact < 0){
        sufficient_battery = false;
      }
      else{
```

```
    float reading = takeReadings(READ_REPS);
    displayForInterval(reading, "data",4000);
    displayForInterval(-1, "clear", 100);

    if(using_modem){
     int msg_len = 140;
     char txtMsg[msg_len];
     String bn, message_text;
     bn = baseNmap(reading);
     message_text = "#cod debug #con xxxxxxxxxxx #mtac " + bn;
     // This command as currently coded will send
     // a coded text message of every reading!!
     openConnection();
     delay(30000);
     sendMessage(selfNum, message_text);
     closeConnection();
    }
   }
  }
  if(bpressed){
   bpressed = false; // reset
   turnOffDisplay();
  }
 }else{
  divisionFactor_TSL230R();
  displayForInterval(-1, "error", 500);
  turnOffDisplay();
  delay(500);
```

```
  }
}

/*-------------------------Voltage Meter Functions--------------------------*/
float divisionFactor_TSL230R(){
  float m = .0052;   //slope of sensor's linear response curve
  float vmin = 3.0;  //min operating v of sensor
  float vmax = 5.5;  //max operating v of sensor
  float v100 = 4.9;  //voltage | normalized response of TSL230r = 1.0
  analogReference(INTERNAL);
  delay(200);
  float v = getVoltageLevel();
  analogReference(DEFAULT);
  delay(200);
  if(v < vmin || v > vmax){return -1;}
  else{return 1 - (4.9 - v) * m;}
}

float getVoltageLevel(){
  float sensorValue = analogRead(VPIN); //drop the first reading
  delay(100);
  sensorValue = float(analogRead(VPIN));
  float divider_value = float(DIV_R2) / float(DIV_R1+DIV_R2);
  float voltage = sensorValue/ 1023.0 * 1.1 / divider_value;
    // normalize by max mapping value, internal reference voltage,
    // and voltage divider, respectively.
  return voltage;
}
```

```
/*------------------------------SevSeg Functions-----------------------------*/
void turnOffDisplay(){
  for(int i = 0; i < num_displays; i++){
    digitalWrite(dispPorts[i], LOW); //turn off digit pins
    }
}

void DisplayADigit(int dispnum, byte digit2disp){
  digitalWrite(shift_latch, LOW);                    //turn shift register off
  turnOffDisplay();
  shiftOut(shift_data, shift_clock, MSBFIRST, digit2disp);     // perform shift
  digitalWrite(shift_latch, HIGH);                    // turn register back on
  digitalWrite(dispnum, HIGH);
  delay(2);                                     // for persistance of vision
}

void SevenSegDisplay(float f, String msg){
  if(msg == "data"){
    long powers[6] = {10000, 1000, 100, 10, 1};
    if(f > 9999){f = 9999.0;}  //bounds checks for display
    if(f < 0){f = 0.0;}
    int numeric_scale = 1, pt = -1, start = 0;
      // determine where to put decimal point and leading blank digit, if needed
    if(f > 1000){;}
    else if(f > 100){
      numeric_scale = 10;
      pt = 2;
```

```
    }else if(f > 10){
      numeric_scale = 100;
      pt = 1;
    }else if(f > 1){
      numeric_scale = 100;
      pt = 1;
      start = 1;
      DisplayADigit(dispPorts[0],SevenSegNumbers[0]);
    }else{
      numeric_scale = 100;
      start = 2;
      DisplayADigit(dispPorts[0],SevenSegNumbers[12]);
      DisplayADigit(dispPorts[1],byte(SevenSegNumbers[0] | SevenSegNumbers[10]));
    }
    long f2l = long(f * numeric_scale);
    for(int i = start; i < 4; i++){
      if(i == pt){
        DisplayADigit(dispPorts[i],SevenSegNumbers[(f2l% powers[i]) / powers[i+1]] |
SevenSegNumbers[10]);
          // perform modulo and integer division calculations to separate digits
          // bit mask with decimal point if needed
      }
      else{
        DisplayADigit(dispPorts[i],SevenSegNumbers[(f2l% powers[i]) / powers[i+1]]);
          //do the above line this way if decimal point not needed for given digit
      }
    }
  }else if(msg == "dashes"){
```

```
  for(int i = 0; i < num_displays; i++){
    DisplayADigit(dispPorts[i],SevenSegNumbers[11]);
  }
}else if(msg == "cycle_dashes"){
  for(int i = 0; i < num_displays; i++){
    DisplayADigit(dispPorts[i],SevenSegNumbers[11]);
    delay(100);
  }
}else if(msg == "ready"){
  // display approximation of "ready" message in Spanish or English
  if(language == "english"){
    DisplayADigit(dispPorts[0],SevenSegLetters[0]);  //r
    DisplayADigit(dispPorts[1],SevenSegLetters[1]);  //E
    DisplayADigit(dispPorts[2],SevenSegLetters[2]);  //d
    DisplayADigit(dispPorts[3],SevenSegLetters[3]);  //Y
  }else if(language == "espanol"){
    DisplayADigit(dispPorts[0],SevenSegLetters[4]);  //L
    DisplayADigit(dispPorts[1],SevenSegLetters[5]);  //S
    DisplayADigit(dispPorts[2],SevenSegLetters[6]);  //t
    DisplayADigit(dispPorts[3],SevenSegLetters[7]);  //O
  }
}else if(msg == "error"){
  // display best available bilingual approximation of "error"
  //  message on seven-segment display
  DisplayADigit(dispPorts[0],SevenSegLetters[1]);  //E
  DisplayADigit(dispPorts[1],SevenSegLetters[0]);  //r
  DisplayADigit(dispPorts[2],SevenSegLetters[0]);  //r
  DisplayADigit(dispPorts[3],SevenSegNumbers[12]);  //
```

```
 }
 else if(msg == "clear"){
   for(int i = 0; i < num_displays; i++){
     DisplayADigit(dispPorts[i],SevenSegNumbers[12]);
   }
 }
}


void displayForInterval(float val, String msg, long ms){
   unsigned long timer = millis();
   while(millis() - timer < ms){SevenSegDisplay(val, msg);}
   turnOffDisplay();
}


/*---------------------Interrupt and TSL230R Functions-----------------------*/
void add_pulse() {pulse_count++;}
 //this simple function counts pulses sent from the sensor


void setSensitivity(int sens){    //set sensor sensitivity
 if(sens == LOW_SENSITIVITY){
   digitalWrite(TSL_S0, LOW);
   digitalWrite(TSL_S1, HIGH);
   sensitivity = LOW_SENSITIVITY;
 }else if(sens == MED_SENSITIVITY){
   digitalWrite(TSL_S0, HIGH);
   digitalWrite(TSL_S1, LOW);
   sensitivity = MED_SENSITIVITY;
 }else if(sens == HIGH_SENSITIVITY){
```

```
    digitalWrite(TSL_S0, HIGH);
    digitalWrite(TSL_S1, HIGH);
    sensitivity = HIGH_SENSITIVITY;
  }
  return;
}

float takeReadings(int num_rdgs){
  digitalWrite(IR_LED, HIGH); //turn on light source
  int rep_cnt = 0, b = 0;
  long sum = 0, low = 1000000, high = 0, rd = 0;
  displayForInterval(-1, "cycle_dashes", 1000);
  PCintPort::attachInterrupt(TSL_FREQ, add_pulse, RISING);
    //turn on frequency-counting function
  delay(200);
  pulse_count = 0; //reset frequency counter
  timer = 0;
  while(rep_cnt < num_rdgs){
    //for given number of readings
    if(millis() - timer >= SAMPLING_WINDOW){
      //once 1000 ms have elapsed
      //normalize frequency by TSL_S2 & TSL_S3 settings
      rd = pulse_count * scale_divider;
      //find highest and lowest readings in the group
      if(rd > high){high = rd;}
      if(rd < low){low = rd;}
      sum += rd;          //sum the readings
      timer = millis();   //update timer
```

```
    rep_cnt++;
    pulse_count = 0;
   }
  }
  PCintPort::detachInterrupt(TSL_FREQ);          //turn off frequency-counting function
  digitalWrite(IR_LED, LOW);                     //turn off light source
  if(num_rdgs > 3){          //chuck out highest and lowest readings and average the rest, if there are four
or more readings
   sum -= (high + low);
   b = 2;
  }

  float raw_value = float(sum) / float(num_rdgs - b) / div_fact, ntu_value = -1;
   // get average reading, with highest and lowest discarded
   // for much higher turbidities, code below could easily be expanded
  // and sensitivity dynamically adjusted
  if(sensitivity == HIGH_SENSITIVITY){
   // map averaged raw sensor value to NTU
   // using calibration info stored in persistent memory
   if(raw_value > config.y4)      {ntu_value = raw_value * config.m4 + config.b4;}
   else if(raw_value > config.y3)  {ntu_value = raw_value * config.m3 + config.b3;}
   else if(raw_value > config.y2)  {ntu_value = raw_value * config.m2 + config.b2;}
   else if(raw_value > config.y1)  {ntu_value = raw_value * config.m1 + config.b1;}
   else                        {ntu_value = raw_value * config.m0 + config.b0;}
   return ntu_value;
  }else{return 9999;}
}
```

```
String baseNmap(float val){
  // baseNmap encodes turbidity values in a base64 cipher,
  // to save space if transmitting many values at once
  int value = (int)(val * 100);
  String enc = "";
  String                                    encoding                                    =
"0123456789abcdefghijklmnopqrstuvwxyzABCDEFGHIJKLMNOPQRSTUVWXYZ/+";
  int base = encoding.length();
  encoding += encoding.substring(0,1);
  long v = value / base;
  long m = value % base;
  while (v > 0){
    enc = encoding.substring(v%base, v%base+1) + enc;
    v = v / base;
  }
  enc += encoding.substring(m%base, m%base+1);
  return enc;
}

/*------------------------------GSM Modem------------------------------------*/
//NOTE: connect the modem to pins 2 (TX), 3 (RX), 7 (RESET), 5V, and GND.
String sendMessage(char* remoteNum, String message){
  sms.beginSMS(remoteNum);  // send the message
  sms.print(message);
  sms.endSMS();
  return "complete";
}
```

```
void openConnection(){
  notConnected = true;
  while (notConnected) {
    digitalWrite(3,HIGH);       // Enable the RX pin
    if(gsmAccess.begin(PINNUMBER)==GSM_READY){notConnected = false;}
    else{delay(1000);}
  }
}

void closeConnection(){
  while(notConnected==false){
    if(gsmAccess.shutdown()==1){
      digitalWrite(3,LOW);      // Disable the RX pin
      notConnected = true;
    }
  }
}
/*---------------------------END---------------------------------*/
```

A.1.1.4 Structural components

The open-source turbidimeter case consists of four different parts: (1) bottom, which includes ports for button and on/off switch; (2) cuvette holder, which houses the sensor and light source and holds the glass cuvette during device operation; (3) top, which has openings for the seven-segment LED display and the top of the cuvette holder; and (4) battery lid, which slides out from the case assembled case top and bottom to expose the battery holder. Electronic files of these objects (in STL format) are available upon request.

Any container that provides good shielding from incidental light may suffice (e.g., a nested pair of cardboard boxes).

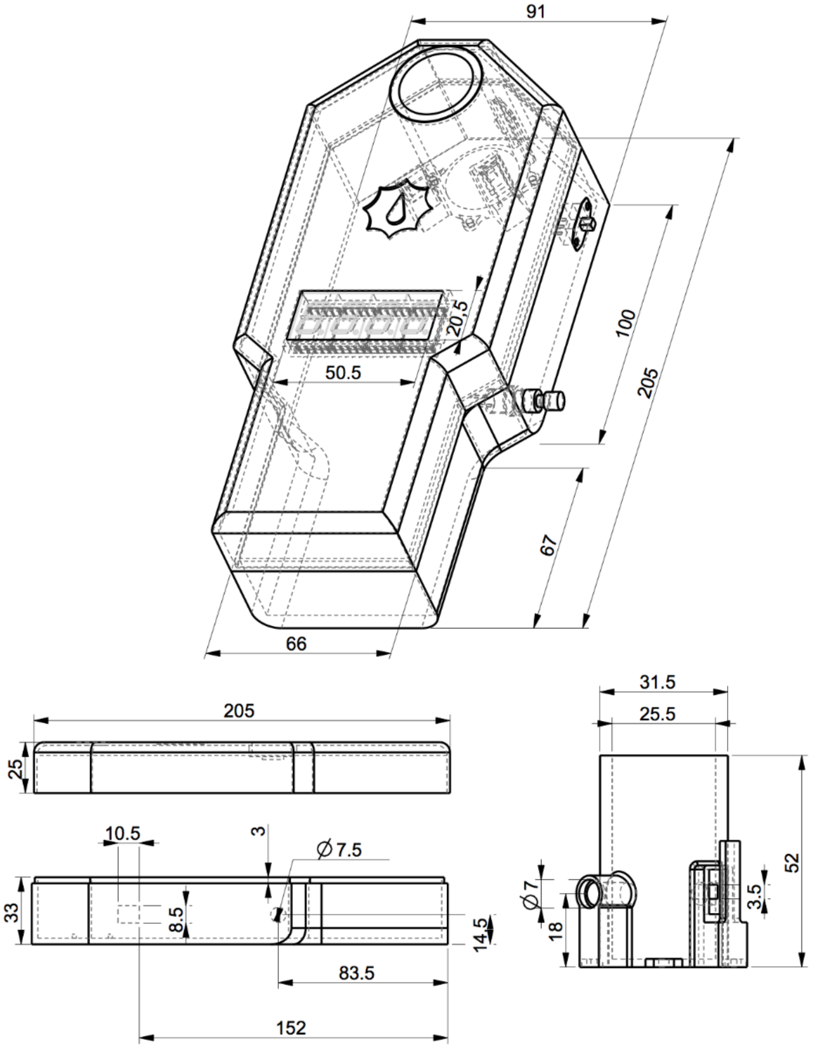


Figure A.3. Image of the open-source turbidimeter with major dimensions given. The four smaller images (left to right) are the case lid (top left), the case base (bottom left), the battery lid (top right), and the cuvette holder (bottom right). All dimensions are in millimeters.

A.1.1.5 Tools required

A utility knife, soldering iron, and solder are required for assembly of the open-source turbidimeter, and safety goggles are recommended. To replicate the printed four-part case, one must have access to a 3D-printer with black ABS filament. The microprocessor can be programmed via a USB-to-Serial adapter (Mouser carries one [#A000059] for $14.95) or with an Arduino (as described at http://arduino.cc/en/Tutorial/ArduinoToBreadboard). Electrical tape is very helpful (for grouping wires together), as are a pair of wire strippers.

A.1.1.6 Assembly

1. Gather the components listed in Section S1, and the tools listed in Section S3.
2. Print the parts described in Section S2 (or devise your own light-shielding case).
3. Wire together the internal components of the open-source turbidimeter according to Figures A1 and A2. Here are some key points:
    a. It's hard to see some connections of the circuit, such as the wiring of the voltage regulator (VR1), on Figure A1. The Arduino website has a well-illustrated tutorial on wiring the ATMega328P microprocessor (http://arduino.cc/en/Main/Standalone) that the reader may find useful.
    b. The semi-circles on the microprocessor (IC1) and shift register (IC2) indicate orientation of these components. It is vital that chips are aligned properly using these guides. Wiring them in the opposite orientation will destroy the chips once voltage is applied! Please note that the semi-circle on the TSL230R sensor in Figure A1 is merely a visual aid, and is not present on the actual chip.
    c. The pins of the seven-segment display are diagrammed by the distributor Electrodragon (http://www.electrodragon.com/w/index.php?title=7-

Segment_Display). The linked document maps pin placement to function and representation in Figure A2 (e.g., the bottom left pin on the seven-segment display is pin 12, which maps to segment E of the display, which connects to port QE on the shift register).

   d. Resistors R2 and R3 combine to form a voltage divider, which is used to measure the voltage provided by the batteries. To achieve useful results, use resistors with tolerance of 1% or less. Tolerance levels of 5% are suitable for the other resistors in the device.
   e. The internal components list generally should be followed closely, however the power switch (S1) and button (S2) can easily be changed to suit the builder's aesthetic.
   f. As always, exercise caution. Do not attempt construction of any electrical device without knowledge of proper technique and safety.

4. Test open-source turbidimeter by placing water sample in glass cuvette, inserting glass cuvette into the device, and analyzing.

   Note: The experiments described in the article were conducted with quartz cuvettes, which may improve optical clarity but at great expense (~$16 each). If using borosilicate cuvettes, it is advisable to calibrate the turbidimeter manually, rather than using the calibration constants provided in section A.1.1.2. When using borosilicate glass cuvettes, it is particularly important to visually inspect the cuvette for scratches, and to always measure turbidity with the cuvette inserted into the sample chamber at the same orientation (this is good advice even with quartz cuvettes). The easiest way to do this is to nick the lid of the cuvette with a knife, and align this nick with the centerline of the turbidimeter case.

A.1.2 Supplementary calibration and validation data

These are available at https://github.com/AWQUA/basic-handheld-turbidimeter/testing.

A.1.3 Field survey questions

The AWQUA Framework (see Chapter 3) stipulates the involvement of third-party testers during the device development process, but does not (yet) address the specific questions that should be asked of device testers or the specific form that their feedback should take. In light of this, a suggested question set for eliciting feedback from third-party tester about both the Affordable Open-Source Turbidimeter and the Black Box handheld turbidimeter is given in Section A.2.3.

A.2 Supplementary information for The Black Box Handheld Turbidimeter

A.2.1 Design

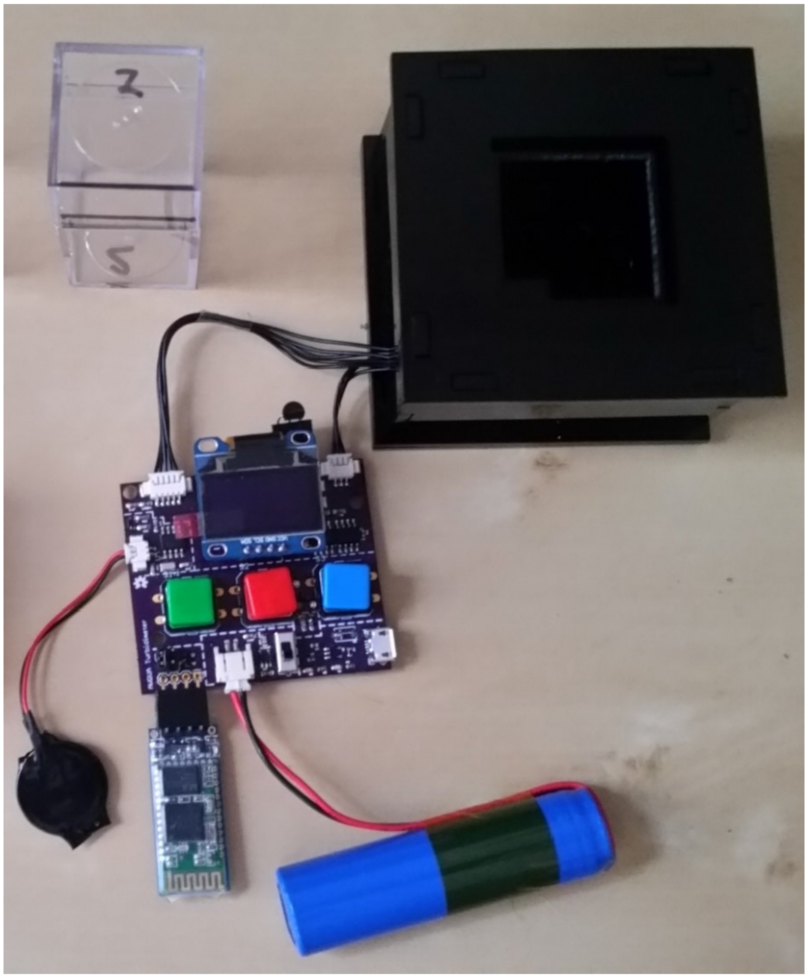


Figure A.4. Photo of a prototype Black Box handheld turbidimeter.

A.2.1.1 Bill of Materials

Table A.2. Bill of materials for the Black Box handheld turbidimeter, showing component cost and price per unit at orders of magnitude.

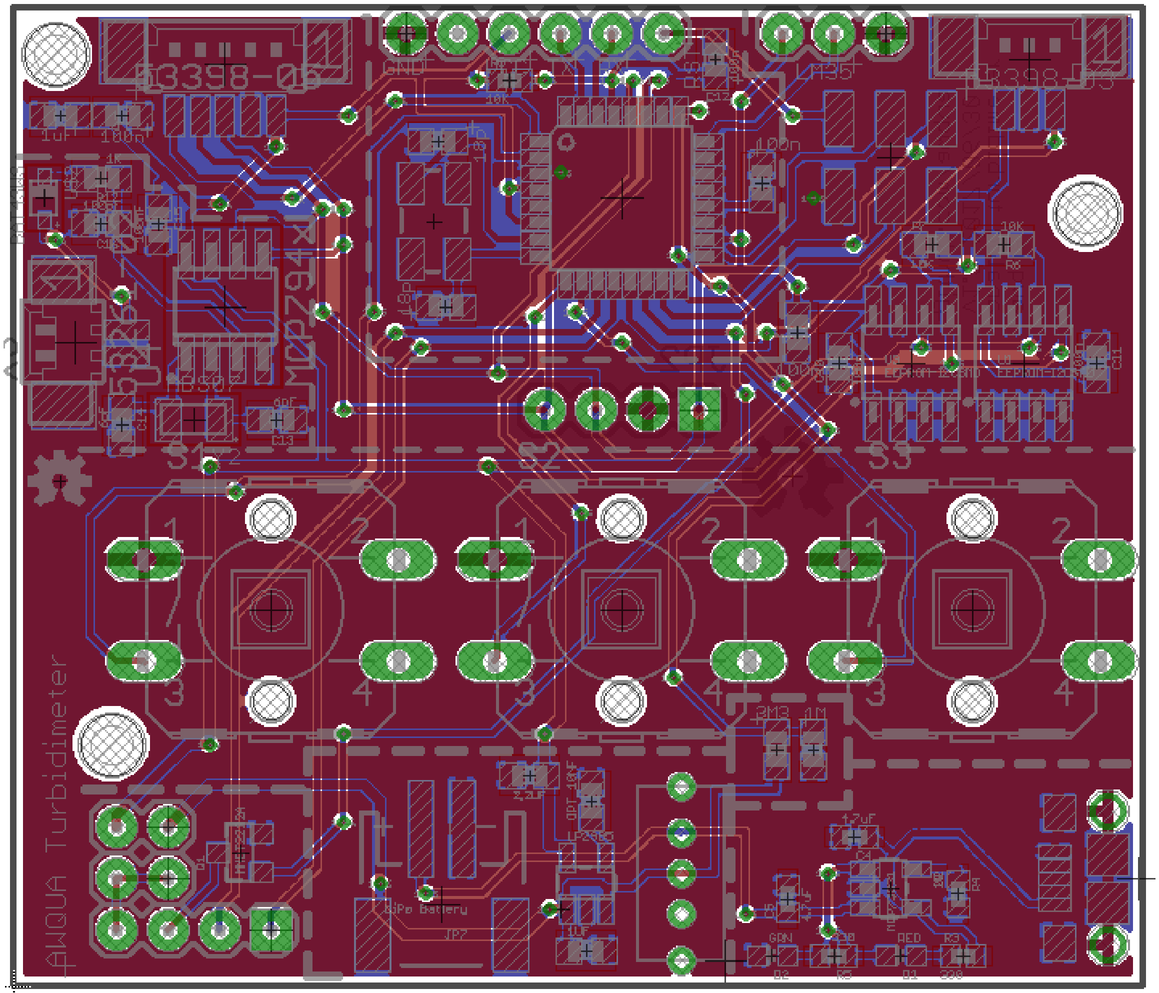
				Price at Quantity ($)		
Qty	**Description**	**Part Number**	**Vendor**	*1*	*10*	*100*
1	49Ohm resistor (+/- 0.1%)	MCT0603PD4999DP500	Mouser	0.57	0.434	0.183
2	330Ohm resistor	RC0603FR-13330RL	Mouser	0.1	0.011	0.004
2	1kOhm resistor	RC0603FR-071KL	Mouser	0.1	0.009	0.003
1	2kOhm resistor	RC0603FR-072KL	Mouser	0.1	0.009	0.003
10	10kOhm resistor	RC0603FR-0710KL	Mouser	0.1	0.009	0.003
2	100kOhm resistor	RC0603FR-07100KL	Mouser	0.1	0.009	0.003
1	1MOhm resistor	RC0603FR-101ML	Mouser	0.1	0.011	0.004
1	3.3MOhm resistor	RC0603FR-073M3L	Mouser	0.1	0.009	0.003
2	6pF capacitor	C1608C0G2A060D080AA	Mouser	0.1	0.054	0.02
2	18pF capacitor	C0603C180J5GACTU	Mouser	0.1	0.037	0.017
1	22pF capacitor	C0603C220J5GACTU	Mouser	0.1	0.046	0.021
1	100pF capacitor	VJ0603A101JXACW1BC	Mouser	0.06	0.06	0.04
1	10nF capacitor	C0603C103K5RACTU	Mouser	0.1	0.021	0.01
11	100nF capacitor	C0603C104Z3VAC	Mouser	0.1	0.01	0.01
4	1uF capacitor	0603ZD105KAT2A	Mouser	0.1	0.1	0.025
1	2.2uF capacitor	EMK107BJ225MA-T	Mouser	0.11	0.046	0.031
4	4.7uF capacitor	LMK107BJ475KA-T	Mouser	0.18	0.069	0.048
1	32kHz clock crystal	ABS07AIG-32.768kHz-7-1-T	Mouser	1.16	1.02	0.84
1	16MHz clock crystal	ECS-160-18-33-JGN-TR	Mouser	0.54	0.45	0.36
1	battery protection diode	BAT43WS-7-F	Mouser	0.37	0.255	0.118
2	NPN transistor	MMBT2222ALT1G	Mouser	0.11	0.092	0.033
1	small green LED	APT1608SGC	Mouser	0.14	0.083	0.068
1	small red LED	AP1608SRCPRV	Mouser	0.13	0.079	0.065
1	860nm IR LED	HIR7393	Mouser	0.5	0.32	0.28
1	IR photodiode	SFH 213 FA	Mouser	0.8	0.654	0.453
1	voltage regulator	AP2112K-3.3TRG1	Mouser	0.47	0.327	0.15
1	battery charge controller	MCP73831T-2ACI/OT	Mouser	0.6	0.56	0.42
1	real-time clock	MCP79412-I/SN	Mouser	1.18	0.98	0.87
2	64kB external memory	24LC512-I/SN	Mouser	1.54	1.28	1.22

Table A.2 (continued). Bill of materials for the Black Box handheld turbidimeter, showing component cost and price per unit at orders of magnitude.

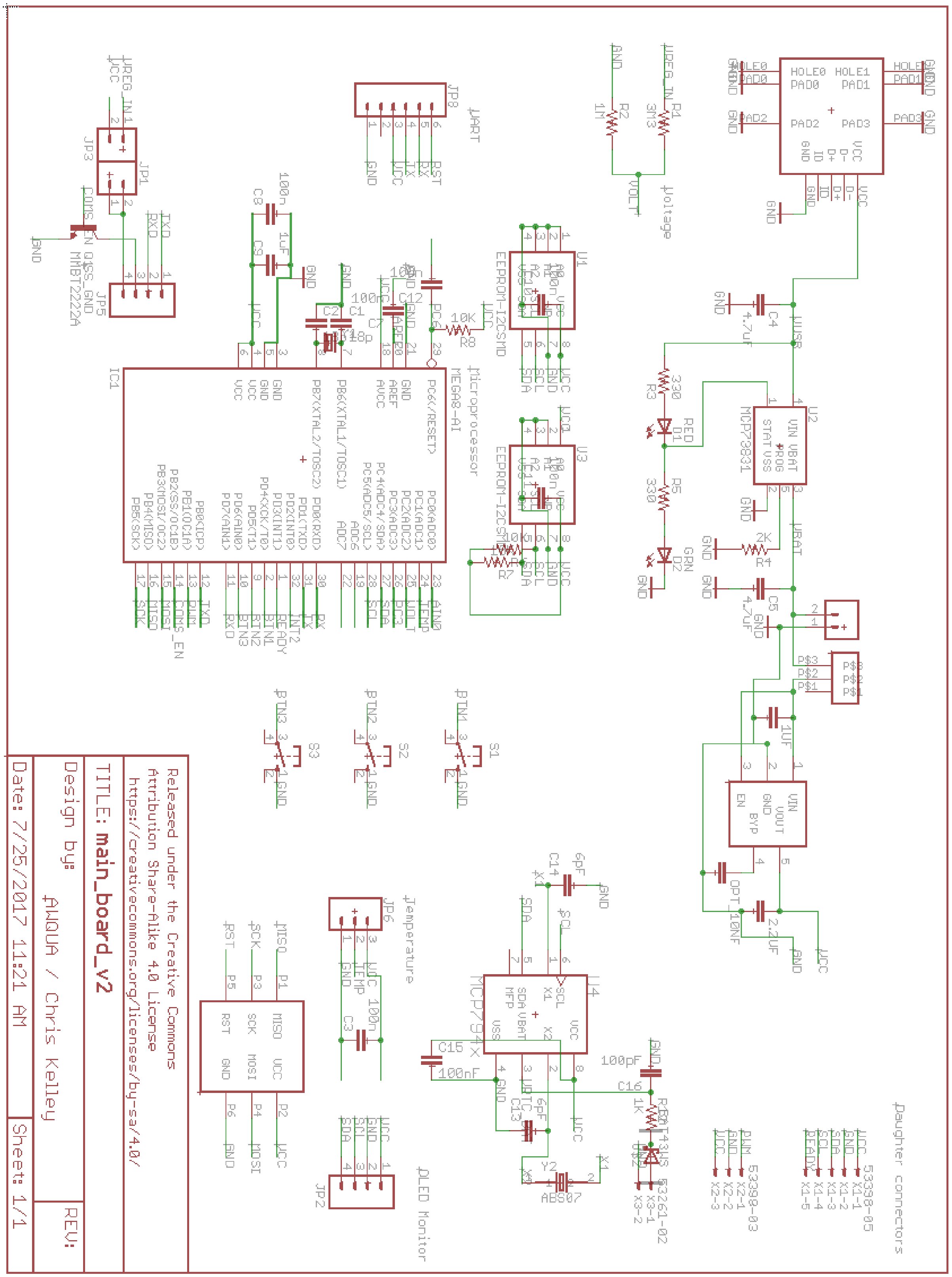
				Price at Quantity ($)		
Qty	**Description**	**Part Number**	**Vendor**	*1*	*10*	*100*
1	temperature sensor	LM35DZ/LFT1	Mouser	2.05	1.61	1.09
2	dual op-amp	OPA2377QDGKRQ1	Mouser	1.84	1.56	1.25
1	analog-to-digital converter	ADS1115IDGSR	Mouser	5.36	4.82	3.95
1	microcontroller	ATMEGA328P-AU	Mouser	2.07	2.07	1.72
1	display	0.96" SSD1306 OLED	Electrodragon	4	4	4
1	Bluetooth unit	HC-06	Alibaba	2.74	2.74	2.74
1	USB micro port	10118193-0001LF	Mouser	0.46	0.375	0.275
1	power switch	OS102011MS2QN1C	Mouser	0.49	0.454	0.4
3	user interface buttons	Omron 12mm round	Adafruit	1.18	1.08	0.92
1	LiPo Battery	LP785060 2500mAh	Alibaba	3.2	3.2	3.2
1	clock battery	CR2032MFR	Mouser	1.21	1.15	1.06
1	clock battery connector	53261-02	Mouser	0.85	0.739	0.643
2	light emitter board port	53261-04	Mouser	1.08	0.936	0.814
2	light detector board port	53261-05	Mouser	1.24	1.09	0.942
1	light emitter board cable	15134-0402	Mouser	2.33	2.12	1.88
1	light detector board cable	15134-0502	Mouser	2.74	2.49	2.21
1	case	laser-cut black acrylic	Acme Plastics	5	5	5
			Cost Per Unit ($):	**$59.01**	**$50.40**	**$43.89**

A.2.1.2 Electronic schematics and wiring

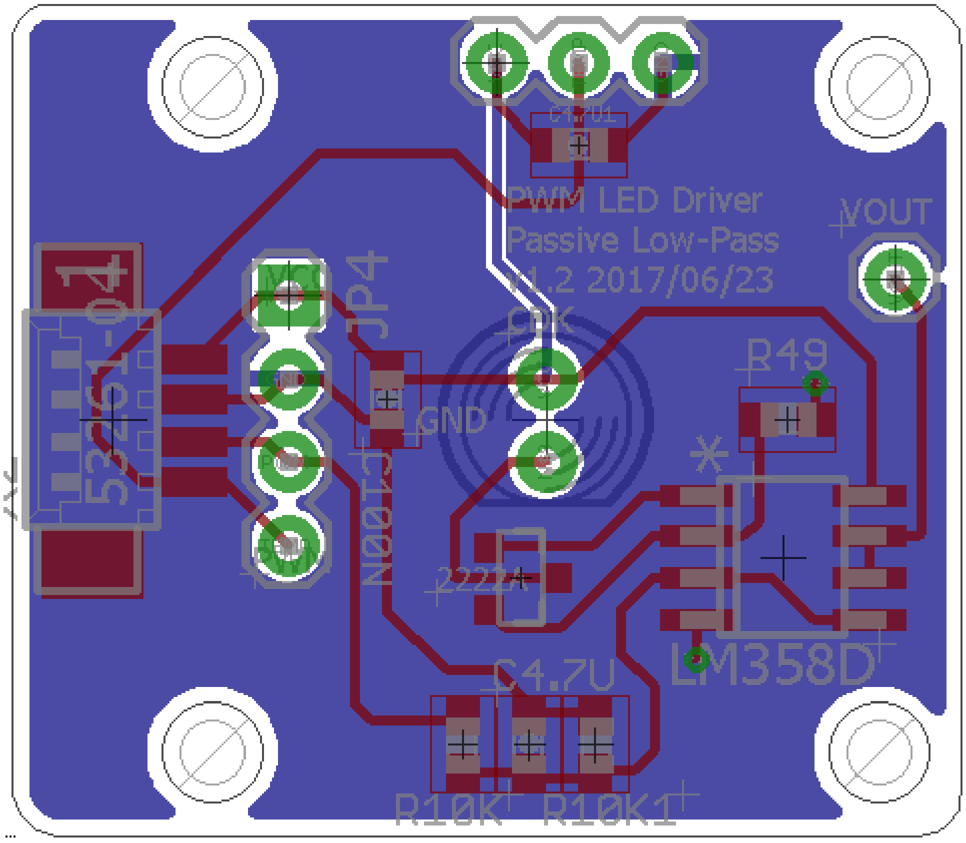
Figure A.5. Circuit boards of the Black Box Handheld Turbidimeter, presented in Eagle schematic and board layouts.



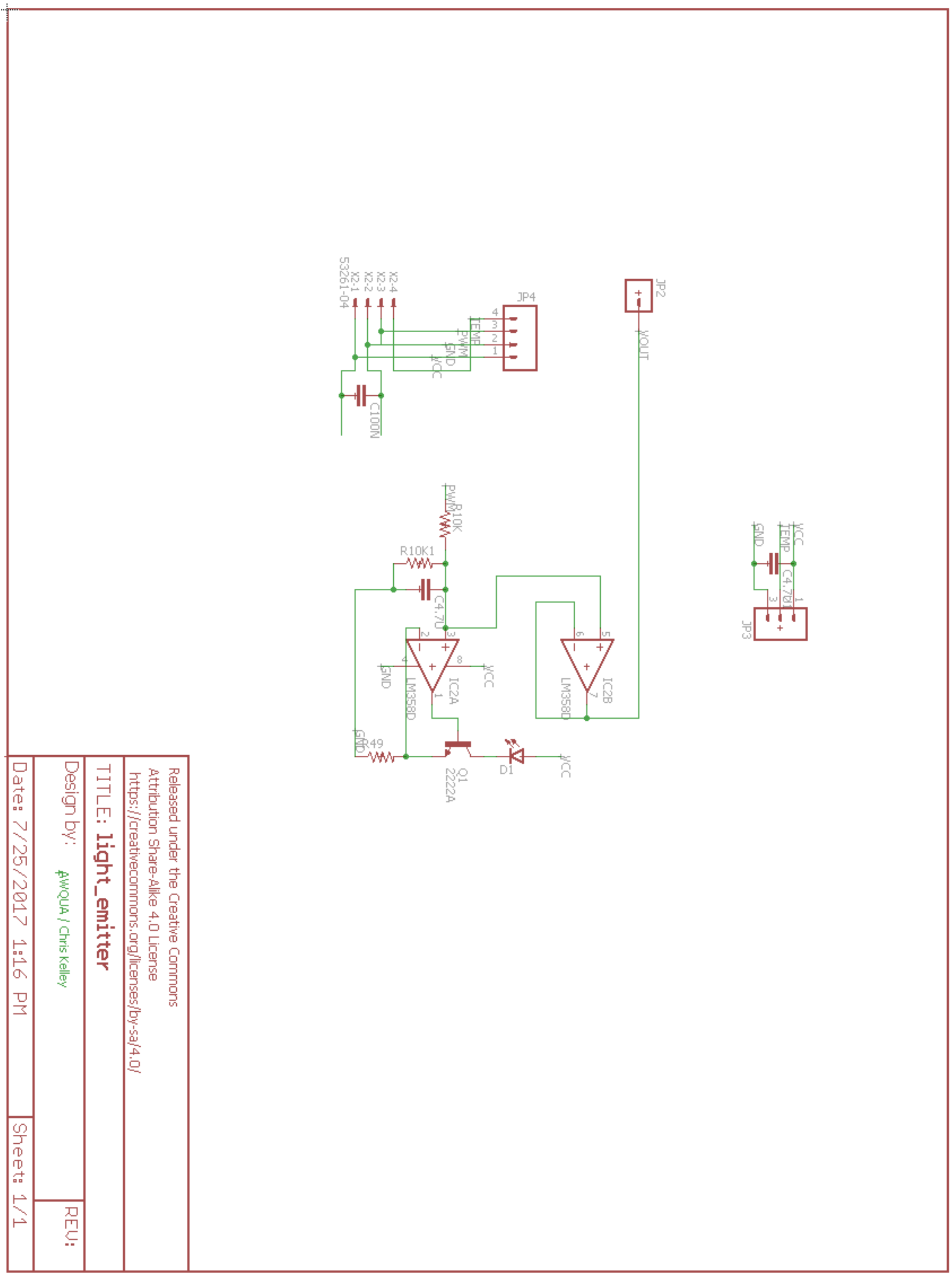
(a) Main circuit board, board layout.



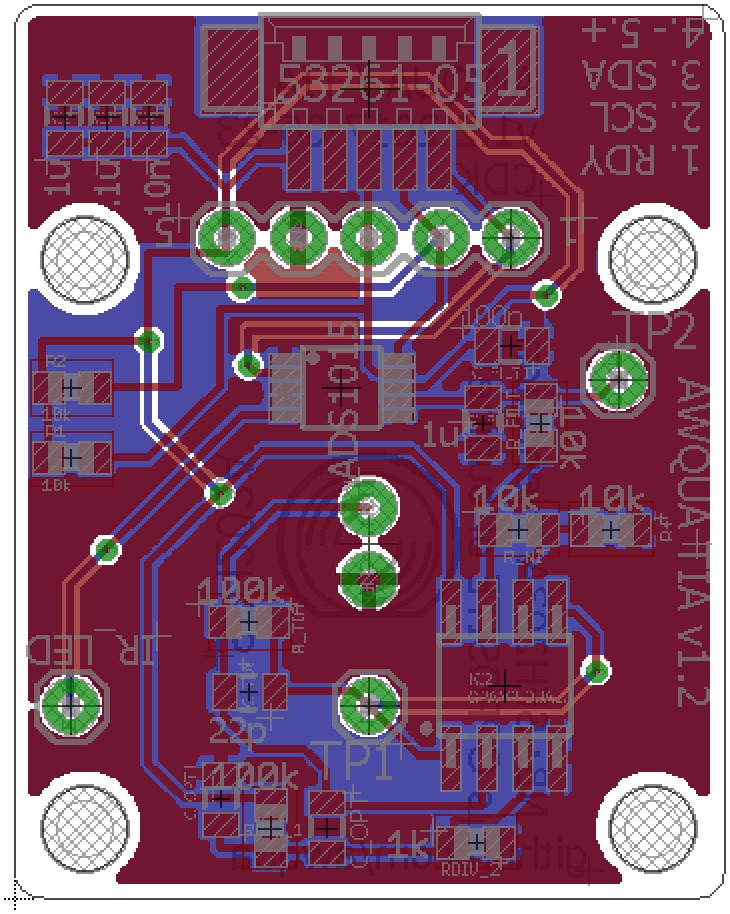
(b) Main circuit board, schematic layout.



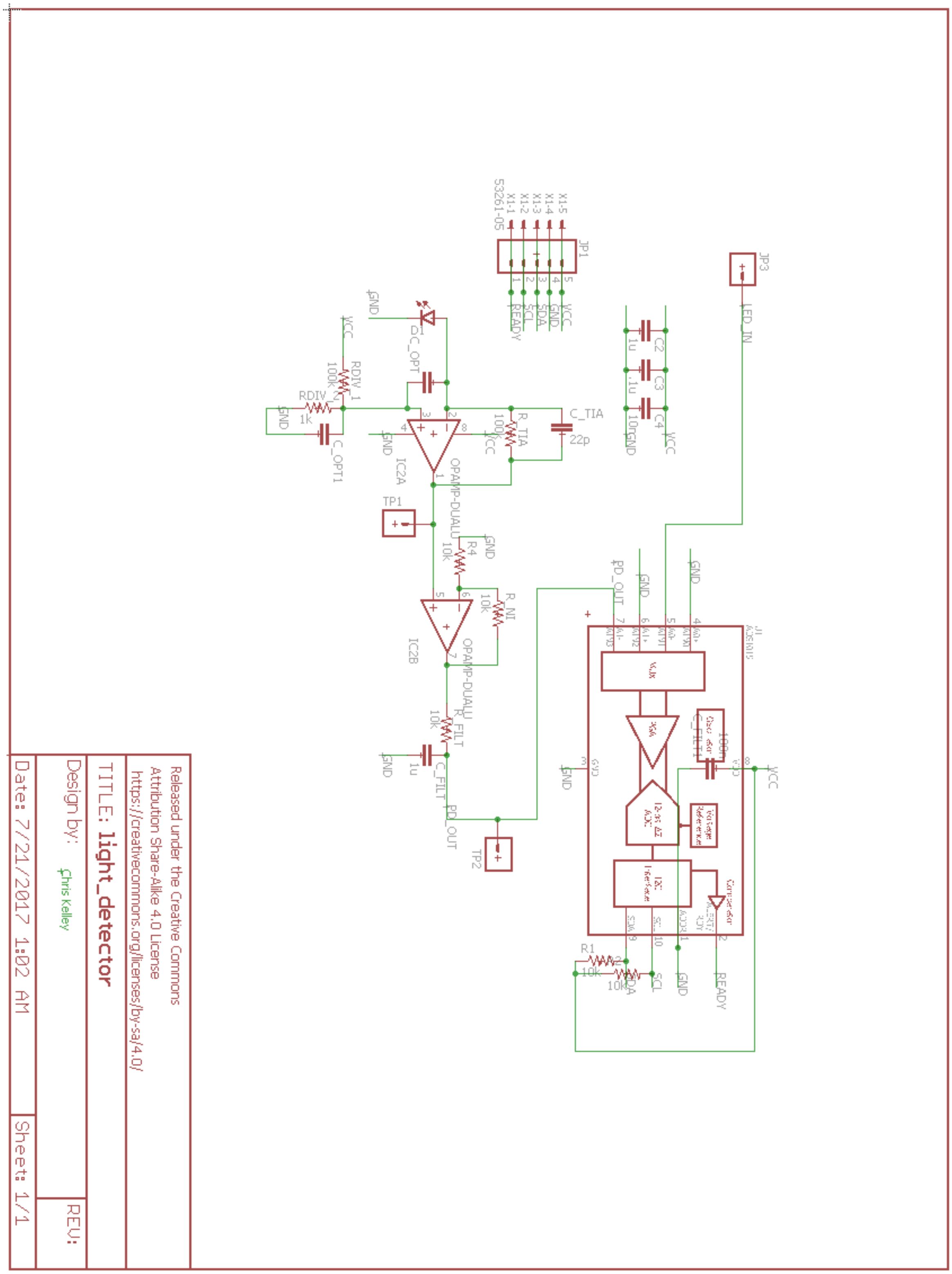
(c) Light emitter, board layout.



(d) Light emitter, schematic layout.



(e) Controls circuit board, board layout.



(f) Light detector, schematic layout.

A.2.1.3 Firmware

A2.1.3.1 SFH213A-based turbidimeter

```
#include <Wire.h>

#include <Adafruit_ADS1015.h>

#include <Statistic.h>

//Fix maxstats so that we analysz and add in readoperation and takereading

//For this version the adc reads from 2 and 3. so be sure to attach photo diodes there

#define NUM_READINGS 10

#define BUTTON1 2

#define LED1 8

#define LED2 9

#define VERB_OFF false

#define VERB_ON true

#define WASTE true

#define NO_WASTE false

#define LED_ON true

#define LED_OFF false

#define LOWER_BOUND 10000

#define UPPER_BOUND 32000


Adafruit_ADS1115 ads;

int gain1, gain2;

float scale1, scale2;

float hist1[NUM_READINGS];

float hist2[NUM_READINGS];

float realval1 = 0.0, realval2 = 0.0;
```

```
boolean button1_press = false;
Statistic realStatOne;
Statistic realStatTwo;
void trigger_button1() {
  button1_press = true;
}

void setup(void) {
  pinMode(BUTTON1, INPUT_PULLUP);
  attachInterrupt(0, trigger_button1, FALLING);
  pinMode(LED1, OUTPUT);
  pinMode(LED2, OUTPUT);
  Serial.begin(9600);
  Serial.println(F("NOTE: is it safe to use GAIN_TWOTHIRDS with an input voltage = 5V?"));
  Serial.println(F("NOTE: why does the voltage dip for one sensor when the other is plugged in? Current
insufficient?"));
 ads.setGain(GAIN_ONE);        // 1x gain   +/- 4.096V  1 bit = 0.125mV
  // ads.setGain(GAIN_TWO);        // 2x gain   +/- 2.048V  1 bit = 0.0625mV
  // ads.setGain(GAIN_FOUR);       // 4x gain   +/- 1.024V  1 bit = 0.03125mV
  // ads.setGain(GAIN_EIGHT);      // 8x gain   +/- 0.512V  1 bit = 0.015625mV
  // ads.setGain(GAIN_SIXTEEN);    // 16x gain  +/- 0.256V  1 bit = 0.0078125mV
  ads.begin();
  delay(20);
  gain1 = ads.getGain();
  gain2 = gain1;
  scale1 = 1.0;
  scale2 = 1.0;
  realStatOne.clear();
```

```
  realStatTwo.clear();
}

void loop (void) {
  if (button1_press) {
    Serial.println("Warmup...");
    read_operation(LED_ON, VERB_OFF, WASTE);
    delay(100);
    Serial.println("Reading...");
    read_operation(LED_ON, VERB_OFF, NO_WASTE);
    delay(100);
    read_operation(LED_OFF, VERB_OFF, NO_WASTE);
    button1_press = false;
    Serial.println("Done!");
  }
  delay(200);
}

void read_operation(boolean leds_on, boolean verbosity, boolean waste) {
  if (leds_on) {
    digitalWrite(LED1, HIGH);
    digitalWrite(LED2, HIGH);
  }
  delay(2);
  for (int i = 0; i < 5; i++) takeReading(verbosity, 1,&gain1,&scale1);
  for (int i = 0; i < NUM_READINGS; i++) {
    hist1[i] = takeReading(verbosity, 1, &gain1, &scale1);
    realStatOne.add(hist1[i]);
```

```
}


for (int i = 0; i < 5; i++) takeReading(verbosity, 2,&gain2,&scale2);
for (int i = 0; i < NUM_READINGS; i++) {
  hist2[i] = takeReading(verbosity, 2, &gain2, &scale2);
  realStatTwo.add(hist2[i]);
}


if(!waste){
  float sd1 = realStatOne.pop_stdev();
  float av1 = realStatOne.average();
  float sd2 = realStatTwo.pop_stdev();
  float av2 = realStatTwo.average();
  Serial.print(F("LED: "));
  if (leds_on) Serial.println("true");
  else Serial.println("false");
  Serial.print(F("Current GAIN1: "));
  Serial.println(gain1);
  Serial.print(F("Current GAIN2: "));
  Serial.println(gain2);
   Serial.println("Summary Data for sensor 1");
  Serial.print(F("Min: "));
  Serial.println(realStatOne.minimum());
  Serial.print(F("Max: "));
  Serial.println(realStatOne.maximum());
  Serial.print(F("Average: "));
  Serial.println(av1);
  Serial.print(F("Standard Dev: "));
```

```
Serial.println(sd1);

Serial.print(F("Variance: "));

Serial.println(realStatOne.variance());

Serial.print(F("Confidence Interval1: ("));

Serial.print(av1 - 1.96 * sd1);

Serial.print(F(","));

Serial.print(av1 + 1.96 * sd1);

Serial.println(F(")"));

Serial.println("Summary Data for sensor 2");

Serial.print(F("Min: "));

Serial.println(realStatTwo.minimum());

Serial.print(F("Max: "));

Serial.println(realStatTwo.maximum());

Serial.print(F("Average: "));

Serial.println(av2);

Serial.print(F("Standard Dev: "));

Serial.println(sd2);

Serial.print(F("Variance: "));

Serial.println(realStatTwo.variance());

Serial.print(F("Confidence Interval2: ("));

Serial.print(av2 - 1.96 * sd2);

Serial.print(F(","));

Serial.print(av2 + 1.96 * sd2);

Serial.println(F(")"));


float nrsum1 = 0.0, zsum1 = 0.0, z1 = 0.0, zcut = 1.5;

float nrsum2 = 0.0, zsum2 = 0.0, z2 = 0.0;
```

```
int reject_count1 = 0;
int reject_count2 = 0;
for (int i = 0; i < NUM_READINGS; i++) {
  z1 = (hist1[i] - av1) / sd1;
  z2 = (hist2[i] - av2) / sd2;
  zsum1 += z1;
  zsum2 +=z2;
  Serial.print(i);
  Serial.print(F(", "));
  Serial.print(hist1[i]);
  Serial.print(F(", "));
  Serial.print(av1);
  Serial.print(F(", "));
  Serial.print(sd1);
  Serial.print(F(", "));
  Serial.print(z1);
  Serial.print(F(", "));
  Serial.print(hist2[i]);
  Serial.print(F(", "));
  Serial.print(av2);
  Serial.print(F(", "));
  Serial.print(sd2);
  Serial.print(F(", "));
  Serial.println(z2);
  if (z1 >= zcut || z1 <= -zcut) {
    ++reject_count1;
  } else {
    nrsum1 += hist1[i];
```

```
      }
      if (z2 >= zcut || z2 <= -zcut) {
        ++reject_count2;
      } else {
        nrsum2 += hist2[i];
      }
    }
    Serial.print(F("Bias 1: "));
    Serial.println(zsum1 * sd1);
    Serial.print(F("Adjusted reading 1: "));
    Serial.println(nrsum1 / (NUM_READINGS - reject_count1));
    Serial.print(F("Bias 2: "));
    Serial.println(zsum2 * sd2);
    Serial.print(F("Adjusted reading 2: "));
    Serial.println(nrsum2 / (NUM_READINGS - reject_count2));
  }
  realStatOne.clear();
  realStatTwo.clear();
  delay(10);
  digitalWrite(LED1, LOW);
  digitalWrite(LED2, LOW);
  delay(2);
}
float takeReading(boolean verbosity, int adc_channel, int *gain, float *scale) {
  int rd, adc;
  float realval;
  adc = ads.readADC_SingleEnded(adc_channel);
  delay(2);
```

```
realval = adc / *scale;
if (verbosity) {
  Serial.print(analogRead(A0));
  Serial.print('\t');
  Serial.print(*gain);
  Serial.print('\t');
  Serial.print(adc);
  Serial.print('\t');
  Serial.println(realval);
}
delay(2);

if (adc > UPPER_BOUND && *gain != GAIN_TWOTHIRDS) {
  switch (*gain) {
    case GAIN_ONE:
      ads.setGain(GAIN_TWOTHIRDS);
      *gain = GAIN_TWOTHIRDS;
      *scale = 0.6667;
      break;
    case GAIN_TWO:
      ads.setGain(GAIN_ONE);
      *gain = GAIN_ONE;
      *scale = 1.0;
      break;
    case GAIN_FOUR:
      ads.setGain(GAIN_TWO);
      *gain = GAIN_TWO;
      *scale = 2.0;
```

```
      break;
    case GAIN_EIGHT:
      ads.setGain(GAIN_FOUR);
      *gain = GAIN_FOUR;
      *scale = 4.0;
      break;
    case GAIN_SIXTEEN:
      ads.setGain(GAIN_EIGHT);
      *gain = GAIN_EIGHT;
      *scale = 8.0;
      break;
  }
  delay(50);
  adc = ads.readADC_SingleEnded(adc_channel);
  delay(2);
  adc = ads.readADC_SingleEnded(adc_channel);
  delay(2);
}
else if (adc < LOWER_BOUND && * gain != GAIN_SIXTEEN) { //adjust gain to a higher mode
  switch (*gain) {
    case GAIN_TWOTHIRDS:
      ads.setGain(GAIN_ONE);
      *gain = GAIN_ONE;
      *scale = 1.0;
      break;
    case GAIN_ONE:
      ads.setGain(GAIN_TWO);
      *gain = GAIN_TWO;
```

```
        *scale = 2.0;
        break;
      case GAIN_TWO:
        ads.setGain(GAIN_FOUR);
        *gain = GAIN_FOUR;
        *scale = 4.0;
        break;
      case GAIN_FOUR:
        ads.setGain(GAIN_EIGHT);
        *gain = GAIN_EIGHT;
        *scale = 8.0;
        break;
      case GAIN_EIGHT:
        ads.setGain(GAIN_SIXTEEN);
        *gain = GAIN_SIXTEEN;
        *scale = 16.0;
        break;
    }
    delay(50);
    adc = ads.readADC_SingleEnded(adc_channel);
    delay(2);
    adc = ads.readADC_SingleEnded(adc_channel);
    delay(2);
  }
  return realval;
}
```

A.2.1.4 Case-rendering code

A.2.1.4.1 OpenSCAD coding of 3D-printed cuvette holder

```
//GLOBALS
$fn = 50;
scl = 1.0;
scale([scl,scl,scl]) turbidimeter_case();
//------------------------------------
//READABLE VARIABLES
cuvette_holder_z = 50;
cuvette_holder_radius = 14.6;

cuvette_chamber_z = 28.4;
cuvette_chamber_radius = 12.3;

cuvette_lip_z = 4;
cuvette_lip_radius = 13.8;

led_mount_x = 11;
led_mount_y = 10;
led_mount_z = 45.2;
led_mount_notch_x = 2.8;
led_mount_notch_z = 1.6;

//ABBREVIATED HELPER VARIABLES
chz = cuvette_holder_z;
ch_r = cuvette_holder_radius;
ccz = cuvette_chamber_z;
ccr = cuvette_chamber_radius;
clz = cuvette_lip_z;
```

```
clr = cuvette_lip_radius;

lmx = led_mount_x;

lmy = led_mount_y;

lmz = led_mount_z;

lmnx = led_mount_notch_x;

lmnz = led_mount_notch_z;

//-------------------------------------

//MODULES

module turbidimeter_case(){

   cuvette_holder();

   case_base();

}


module case_base(){

   difference(){

      translate([0,0,1])oval(32,25,2);

      translate([-50,-38,0])cube([100,20,3]);

   }

}



//INDIVIDUAL PARTS

module cuvette_holder(){

   difference(){

      union(){

         cylinder(r=ch_r,h=chz);

         translate([ch_r-2,-lmy/2,0]) led_mount();

         translate([-ch_r+2,lmy/2,0]) rotate([0,0,180]) led_mount();
```

```
            translate([-ch_r+9,lmy/2+8,0]) rotate([0,0,135]) led_mount();

            translate([-25,-ch_r,0]) pcb_mount();

        }

        translate([0,0,chz-ccz]) cylinder(r=ccr, h=ccz);

        translate([0,0,chz-clz]) cylinder(r=clr, h=clz);

    }

}


module pcb_mount(){

    TPZO = 8;  //temp pcb z-offset

    difference(){

        cube([50,2,lmz]);

        translate([10,0,6]) rotate([90,0,0]) cylinder(r=1.2,h=4, center=true);

        translate([10,0,20]) rotate([90,0,0]) cylinder(r=1.2,h=4, center=true);


        translate([3,0,31+TPZO]) rotate([90,0,0]) cylinder(r=1.2,h=4, center=true);

        translate([6,0,22+TPZO]) rotate([90,0,0]) cylinder(r=1.2,h=4, center=true);

        translate([50-3,0,31+TPZO]) rotate([90,0,0]) cylinder(r=1.2,h=4, center=true);

        translate([50-6,0,22+TPZO]) rotate([90,0,0]) cylinder(r=1.2,h=4, center=true);


        translate([21.5,0,18.25+TPZO]) cube([9,2,10]);

    }

}


module led_mount(){

    difference(){

        cube([lmx,lmy,lmz]);

        translate([12.2,lmy/2-4,20]) rotate([0,0,90]) led_backpack();
```

```
        translate([lmx/2-lmnx/2,0,lmz-lmnz]) cube([lmnx,lmy,lmnz]);
    }
}

module led_backpack(){
    cube([8,2,21]);
    translate([0,2,4]) cube([8,2,4]);
    rotate([90,0,0]) translate([4,13,-2.5]) cylinder(r = 3.5,h = 1, center = true);
    rotate([90,0,0]) translate([4,13,-8]) cylinder(r = 3, h = 10,center = true);
    rotate([90,0,0]) translate([4,19,-6]) cylinder(r = 1.5,h = 8,center = true);
    rotate([90,0,0]) translate([4,2,-6]) cylinder(r = 1.5,h = 8,center = true);
}

module oval(w,h, height, center = true) {
    scale([1, h/w, 1]) cylinder(h=height, r=w, center=center);
}
```

A.2.1.4.2 PaperJS coding of laser-cut cuvette holder

```
//Passing to Inkscape for normal laser-cutting toolchain
//Describing shape in tenths of a millimeter
//Inkscape (v<0.91) assumes 90 pixels : 1 inch
//So scale factor = 90 / 254 = 0.35433          //.37795 for Inkscape > v.91

var scale = .35433;             //pixel to .1mm
var cuv_height = 540;
var cuv_diam = 246; //254
var cuv_lid_diam = 272; //280
var lip_height = 30;
```

```
var ridge_width = 90;

var width = 400;

var top_width = 520;

var led_diam = 50;

var led_offset = 15;

var screwhole_diam = 30;

var screwhole_offset = 85;

var end_screwhole_offset = 40;

var height = cuv_height + lip_height*4;

var gap_width = width - 4 * lip_height - 2 * ridge_width;

var side_offset = width * 1.8;

var top_offset = new Point(0,width * 1.1);//-(top_width - width)/2,-(top_width - width)/2);

var origin = new Point(0,0);


var build_end = function(){

    var top_end = new Path.Rectangle(new Point(0,0), new Point(top_width,top_width));

    top_end.strokeColor = 'black';


    var top_slot1 = new Path.Rectangle(new Point(0,0), new Point(ridge_width,lip_height));

    top_slot1.strokeColor = 'black';

    top_slot1.translate(new Point(top_width/2, top_width/2));

    var top_slot2 = top_slot1.clone();

    var top_slot3 = top_slot1.clone();

    var top_slot4 = top_slot1.clone();

    var top_slot5 = top_slot1.clone();

    top_slot1.translate(new Point(-gap_width/2 - ridge_width,-width/2));

    top_slot2.translate(new Point(gap_width/2, -width/2));

    top_slot3.translate(new Point(gap_width/2, width/2 - lip_height));
```

```
    top_slot4.translate(new Point(-gap_width/2 - ridge_width, width/2 - lip_height));
    top_slot5.rotate(-90);
    top_slot5.translate(-top_slot5.bounds._height/2, -top_slot5.bounds._width/2);
    top_slot5.translate(new Point(-width/2 + lip_height/2, -(gap_width + ridge_width)/2));
    var top_slot6 = top_slot5.clone();
    var top_slot7 = top_slot5.clone();
    var top_slot8 = top_slot5.clone();
    top_slot6.translate(new Point(width - lip_height, 0));
    top_slot7.translate(new Point(0,gap_width + ridge_width));
    top_slot8.translate(new Point(width - lip_height,gap_width + ridge_width));

    var top_hole = new Path.Circle({center: new
Point(top_end.bounds._width/2,top_end.bounds._height/2),radius: cuv_lid_diam/2});
    top_hole.strokeColor = 'black';


    top_end.translate(top_offset);
    top_hole.translate(top_offset);
    top_slot1.translate(top_offset);
    top_slot2.translate(top_offset);
    top_slot3.translate(top_offset);
    top_slot4.translate(top_offset);
    top_slot5.translate(top_offset);
    top_slot6.translate(top_offset);
    top_slot7.translate(top_offset);
    top_slot8.translate(top_offset);

    var end_screwhole1 = new Path.Circle({center: new Point(0,0), radius: screwhole_diam/2});
    end_screwhole1.translate(top_offset,0);
```

```
    end_screwhole1.strokeColor = 'black';
    var end_screwhole2 = end_screwhole1.clone().translate(top_end.bounds._width - end_screwhole_offset,end_screwhole_offset);
    var end_screwhole3 = end_screwhole1.clone().translate(top_end.bounds._width - end_screwhole_offset,top_end.bounds._width - end_screwhole_offset);
    var end_screwhole4 = end_screwhole1.clone().translate(end_screwhole_offset,top_end.bounds._width - end_screwhole_offset);
    end_screwhole1.translate(end_screwhole_offset,end_screwhole_offset);

}

var build_side = function(){
    var side_top_seg = [
        new Point(lip_height, lip_height),
        new Point(lip_height*2, lip_height),
        new Point(lip_height*2, 0),
        new Point(lip_height*2 + ridge_width, 0),
        new Point(lip_height*2 + ridge_width, lip_height),
        new Point(lip_height*2 + ridge_width + gap_width, lip_height),
        new Point(lip_height*2 + ridge_width + gap_width, 0),
        new Point(lip_height*2 + ridge_width*2 + gap_width, 0),
        new Point(lip_height*2 + ridge_width*2 + gap_width, lip_height),
        new Point(width, lip_height),
    ];

    var side_top = new Path(side_top_seg);
    side_top.strokeColor = 'black';
    side_top.position = new Point(side_offset,lip_height/2);
```

```
    var side_bottom = side_top.clone();
    side_bottom.scale(-1,1);
    side_bottom.rotate(180);
    side_bottom.position = new Point(side_offset,height + lip_height *1.5);

    var side_left = new Path();
    side_left.add(new Point (0,0));
    side_left.add(new Point (0,height));
    side_left.strokeColor = 'black';
    side_left.position = new Point(side_offset - side_top.bounds._width / 2, height / 2 + lip_height)
    var side_right = side_left.clone();
    side_right.position = new Point(side_offset + side_top.bounds._width / 2, height / 2 + lip_height);

    var hole1 = new Path.Rectangle(new Point(0,0), new Point(ridge_width,lip_height));
    hole1.strokeColor = 'black';
    hole1.position = new Point(side_offset - side_top.bounds._width/2 + lip_height + ridge_width/2, 2 *
lip_height + hole1.bounds._height/2);
    var hole2 = hole1.clone();
    var hole3 = hole1.clone();
    var hole4 = hole1.clone();
    var hole5 = hole1.clone();
    var hole6 = hole1.clone();
    hole2.translate(new Point(gap_width + ridge_width,0));
    hole3.translate(new Point(0,cuv_height/2));
    hole4.translate(new Point(gap_width + ridge_width,cuv_height/2));
    hole5.translate(new Point(0,cuv_height + lip_height));
    hole6.translate(new Point(gap_width + ridge_width,cuv_height + lip_height));
```

```
    var led_hole = new Path.Circle({center: new Point(0,0), radius: led_diam/2});
    led_hole.position = new Point(-side_top.bounds._width / 2 + lip_height + ridge_width + gap_width/2,
led_offset + cuv_height * .78 + lip_height * 2);
    led_hole.translate(side_offset,0);
    led_hole.strokeColor = 'black';


    var bpw34_sensor_hole = new Path.Rectangle(new Point(0,0), new Point(50,50));
    bpw34_sensor_hole.position = new Point(-side_top.bounds._width / 2 + lip_height + ridge_width +
gap_width/2, cuv_height * .78 + lip_height * 2);
    bpw34_sensor_hole.translate(side_offset,0);
    bpw34_sensor_hole.strokeColor = 'black';


    var pcb_screwhole1 = new Path.Circle({center: new Point(0,0), radius: screwhole_diam/2});
    pcb_screwhole1.position = new Point(-side_top.bounds._width / 2 + lip_height + ridge_width +
gap_width/2,cuv_height * .78 + lip_height * 2);
    pcb_screwhole1.translate(side_offset,0);
    pcb_screwhole1.strokeColor = 'black';
    var pcb_screwhole2 = pcb_screwhole1.clone().translate(-screwhole_offset,-screwhole_offset);
    var pcb_screwhole3 = pcb_screwhole1.clone().translate(screwhole_offset,-screwhole_offset);
    var pcb_screwhole4 = pcb_screwhole1.clone().translate(-screwhole_offset,screwhole_offset);
    var pcb_screwhole5 = pcb_screwhole1.clone().translate(-screwhole_offset,led_offset-screwhole_offset);
    var pcb_screwhole6 = pcb_screwhole1.clone().translate(screwhole_offset,led_offset-screwhole_offset);
    var pcb_screwhole7 = pcb_screwhole1.clone().translate(-screwhole_offset,screwhole_offset-led_offset);
    var pcb_screwhole8 = pcb_screwhole1.clone().translate(screwhole_offset,screwhole_offset-led_offset);
    pcb_screwhole1.translate(screwhole_offset,screwhole_offset);



}
```

```
var build_middle = function(){
    var middle_outside_seg = [
        new Point(lip_height, lip_height),
        new Point(lip_height * 2, lip_height),
        new Point(lip_height * 2, 0),
        new Point(lip_height * 2 + ridge_width, 0),
        new Point(lip_height * 2 + ridge_width, lip_height),
        new Point(lip_height * 2 + ridge_width + gap_width, lip_height),
        new Point(lip_height * 2 + ridge_width + gap_width, 0),
        new Point(width - lip_height * 2, 0),
        new Point(width - lip_height * 2, lip_height),
        new Point(width - lip_height, lip_height)
    ];
    var middle_outside = new Path(middle_outside_seg);

    var middle_inside_center = new Point(width/2,width/2);

    var middle_inside = new Path.Circle({center: origin,radius: cuv_diam/2});
    middle_outside.strokeColor = 'black';
    middle_inside.strokeColor = 'black';
    middle_outside.position = new Point((width - lip_height*2)/2 + lip_height, lip_height/2);
    middle_inside.position = middle_inside_center;
    middle_outside2 = middle_outside.clone();
    middle_outside3 = middle_outside.clone();
    middle_outside4 = middle_outside.clone();
    middle_outside2.position = new Point((width - lip_height*2)/2 + lip_height, width - lip_height/2);
    middle_outside2.rotation = 180;
```

```
    middle_outside3.position = new Point(lip_height/2,width/2);
    middle_outside3.rotation = -90;
    middle_outside4.position = new Point(width - lip_height/2,width/2);
    middle_outside4.rotation = 90;
}


var downloadAsSVG = function (fileName) {
   if(!fileName) {fileName = "paperjs_example.svg"}
   var url = "data:image/svg+xml;utf8," +
encodeURIComponent(paper.project.exportSVG({asString:true}));
   var link = document.createElement("a");
   link.download = fileName;
   link.href = url;
   link.click();
}
//-----------------------------------------------
build_middle();
build_side();
build_end();
```

A.2.1.5 Tools required

A solder paste syringe, tweezers, an electric skillet, a toothbrush, and 70% isopropyl rubbing alcohol are needed for constructing the circuit boards. An electric fan is recommended if the work area does not have high ventilation. A laser cutter (recommended 40W laser or greater) is used to cut the case.

A.2.1.6 Assembly

The case-rendering code in Section A.2.1.4 can be run in a PaperJS client (e.g. in a web browser window) to produce an SVG file that can be used to guide a laser cutter (the toolchain from SVG to laser cutting depends on the manufacturer of the laser cutter). The current prototype of the Black Box handheld turbidimeter, at the time of writing, does not have solid fasteners to attach the pieces of its case; these pieces are friction-fitted and may be additionally secured using a suitable epoxy.

To prepare the circuit boards, first procure the components outlined in the Bill of Materials given in Table A.2. Given the compact board design and small components utilized, it is recommended that the circuit boards be professionally manufactured rather than etched at home. The circuit boards have been successfully assembled for prototypes using only a solder syringe and tweezers for the surface-mount components (cooking the board in a typical covered electric skillet), and a soldering iron for the through-hole components. Tutorials for through-hole and surface-mount soldering are beyond the scope of this document but may be readily found online and in print.

Connect the clock battery to the two-pin connector on the main board, and then connect the Bluetooth unit to the connector on the bottom left-hand corner of the main board. The light emitter and light detector boards connect to the main board via four-wire and five-wire cables, respectively. Finally, connect the light emitter and light detector boards to the appropriate inner walls of the case using twisted wire, screws and nuts, or epoxy before closing the outer wall of the case.

A.2.2 Field survey questions

Device ease of use

I found it easy to use the device today

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree
(5) Strongly agree

I was frustrated using the device today

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I was able to collect all the readings I needed

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

Additional comments on device ease of use:

Device ergonomics

I was able to read the words on the display.

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree

(5) Strongly agree

The text that the device displayed made sense to me.

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I was able to easily turn the device on and off

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I was able to easily use the buttons on the device

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

Additional comments on device ergonomics:

User knowledge

I know how to use this device to measure turbidity

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I have viewed a video tutorial for how to use this device

(1) Yes
(2) No

I know how to re-calibrate this device

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I have viewed a video tutorial for how to re-calibrate this device

(1) Yes
(2) No

I know how to check the temperature and voltage level of the device

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I know how to recharge this device

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I know where I can get this device repaired

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

Additional comments about user knowledge:

Data collection form

Date	Time	Temperature	Voltage	Turbidity	Operator Name

I have completed the data collection form today

(1) Yes

(2) No

I found it easy to complete this form today

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I was frustrated completing this form today

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

Additional comments about data collection form

Appendix B. Supplementary information for Chapter 6

B.1 Design of the Monocle inline turbidimeter

Figure B1. Exterior of Monocle Inline Turbidimeter.

B1.1.1 Bill of Materials

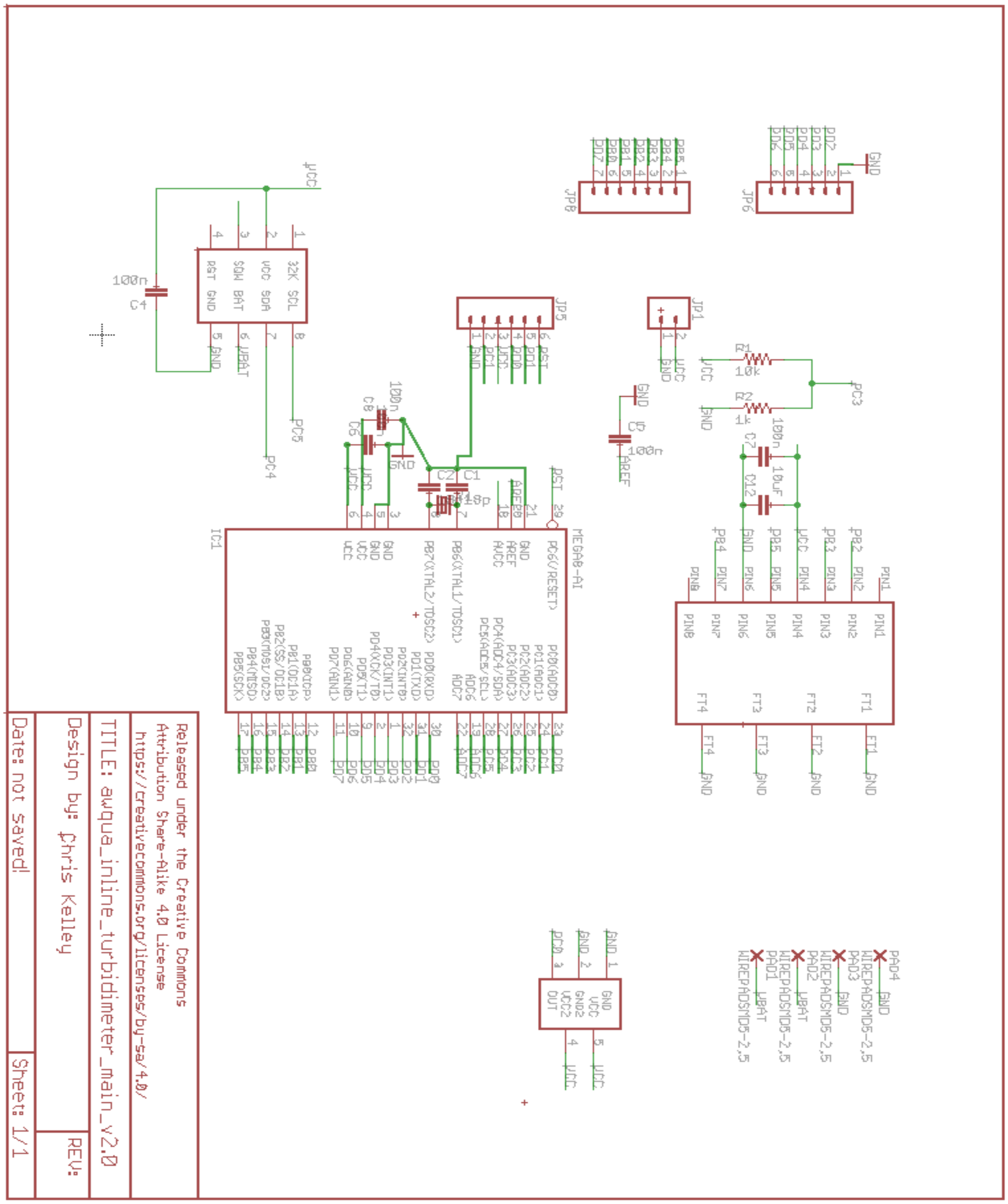
Table B.1. Bill of materials for Monocle Inline Turbidimeter, showing component cost and aggregate price per unit at orders of magnitude.

			Price at Quantity ($)						
Qty	**Name**	**Description**	*1*	*10*	*100*	*250*	*500*	*1000*	*10000*
2	C1,C2	18pF Capacitor	0.1	0.022	0.015	0.015	0.015	0.01	0.007
6	C4-C8	0.1uF Capacitor	0.1	0.021	0.014	0.014	0.014	0.009	0.009
1	C9	10uF Capacitor	0.19	0.079	0.055	0.055	0.055	0.046	0.026
1	C10	1uF Capacitor	0.1	0.036	0.016	0.016	0.016	0.009	0.006
1	C11	2.2uF Capacitor	0.12	0.046	0.032	0.032	0.032	0.022	0.017
2	C12-C13	4.7uF Capacitor	0.16	0.062	0.043	0.043	0.043	0.029	0.023
1	C14	10nF Capacitor	0.1	0.01	0.006	0.006	0.006	0.005	0.005
1	IC1	8-bit Microcontroller	2.07	2.07	1.72	1.72	1.72	1.64	1.64
1	M-SD	MicroSD Holder	1.26	1.11	0.958	0.871	0.713	0.634	0.574
1	R1	10K 1% Resistor	0.1	0.01	0.003	0.003	0.003	0.002	0.001
1	R2	1K 1% Resistor	0.1	0.01	0.003	0.003	0.003	0.002	0.001
1	R3	2K 1% Resistor	0.1	0.01	0.003	0.003	0.003	0.002	0.001
2	R4-R5	330 Resistor	0.1	0.01	0.003	0.003	0.003	0.002	0.001
1	JPx	16 Header Pins	0.61	0.514	0.468	0.468	0.422	0.395	0.35
1	HS1	Header Socket	0.11	0.11	0.11	0.11	0.11	0.11	0.11
1	T1	+/- 0.5C Temperature Sensor	0.86	0.712	0.442	0.442	0.442	0.306	0.306
1	Q1	16MHz Crystal	0.73	0.618	0.493	0.493	0.493	0.376	0.329
1	S1	Light-to-Frequency Sensor	3.87	3.46	2.84	2.56	2.29	1.93	1.86
1	RTC	Real-Time Clock	7.51	7.14	5.72	5.45	5.23	4.04	4.04
4	L1-L4	IR LED	0.5	0.32	0.28	0.28	0.28	0.164	0.135
4	D1-D4	Current-Limiting Diode	0.49	0.406	0.248	0.248	0.248	0.191	0.151
1	USB1	MicroUSB Port	0.46	0.318	0.274	0.274	0.261	0.261	0.158
1	VR1	3.3V Voltage Regulator	0.55	0.465	0.3	0.3	0.3	0.24	0.194
1	DS1	Voltage-Protection Diode	0.46	0.329	0.151	0.151	0.151	0.116	0.09
1	BC1	LiPo Battery Charger	0.6	0.56	0.42	0.42	0.42	0.42	0.42
1	BT1	LiPo Battery Terminal	0.556	0.54	0.338	0.338	0.338	0.274	0.274
1	BATT	LiPo Battery	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1	VLF1	Visible Light Filter	12.75	1.275	0.255	0.255	0.255	0.255	0.255
1	PCB1	Main Circuit Board	5.97	0.597	0.358	0.5	0.42	0.371	0.288
1	PCB2	Power Circuit Board	5.97	0.597	0.179	0.208	0.25	0.168	0.115
1	PCB3	Sensor Circuit Board	5.97	0.597	0.179	0.537	0.25	0.244	0.208
1	XT1	Exterior Case	5.04	4.41	3.04	2.56	2.44	2.08	2
1	XT2	Case Gasket	4.31	3.77	2.35	2.35	2.35	2.35	2.35
1	INVP1	Inventory Planning	22.5	2.25	0.225	0.09	0.045	0.0225	0.00225
1	PCBAA	Assembly, Option A	*561.98*	67.92	10.02	8.16	6.94	6.42	6.22
1	PCBAB	Parts & Assembly, Option B	*436.62*	43.66	27.95	26.91548	25.4794	22.33	21.85
1	PCBAC	Self Assembly, Option C	20	15.5	15.5	15.5	15.5	15.5	15.5
1	PCBAC	Final Assembly	7.5	7.5	7.5	7.5	7.5	7.5	7.5
1	CAL1	Device Calibration	11.25	11.25	11.25	11.25	11.25	11.25	11.25
		Unit cost, Option A ($):	**$671.48**	**$124.03**	**$54.53**	**$51.94**	**$49.53**	**$45.55**	**$44.35**
		Unit cost, Option B ($):	**$480.19**	**$73.77**	**$54.04**	**$52.53**	**$50.93**	**$46.93**	**$46.21**
		Unit cost, Option C ($):	**$129.50**	**$71.61**	**$60.01**	**$59.28**	**$58.09**	**$54.63**	**$53.63**

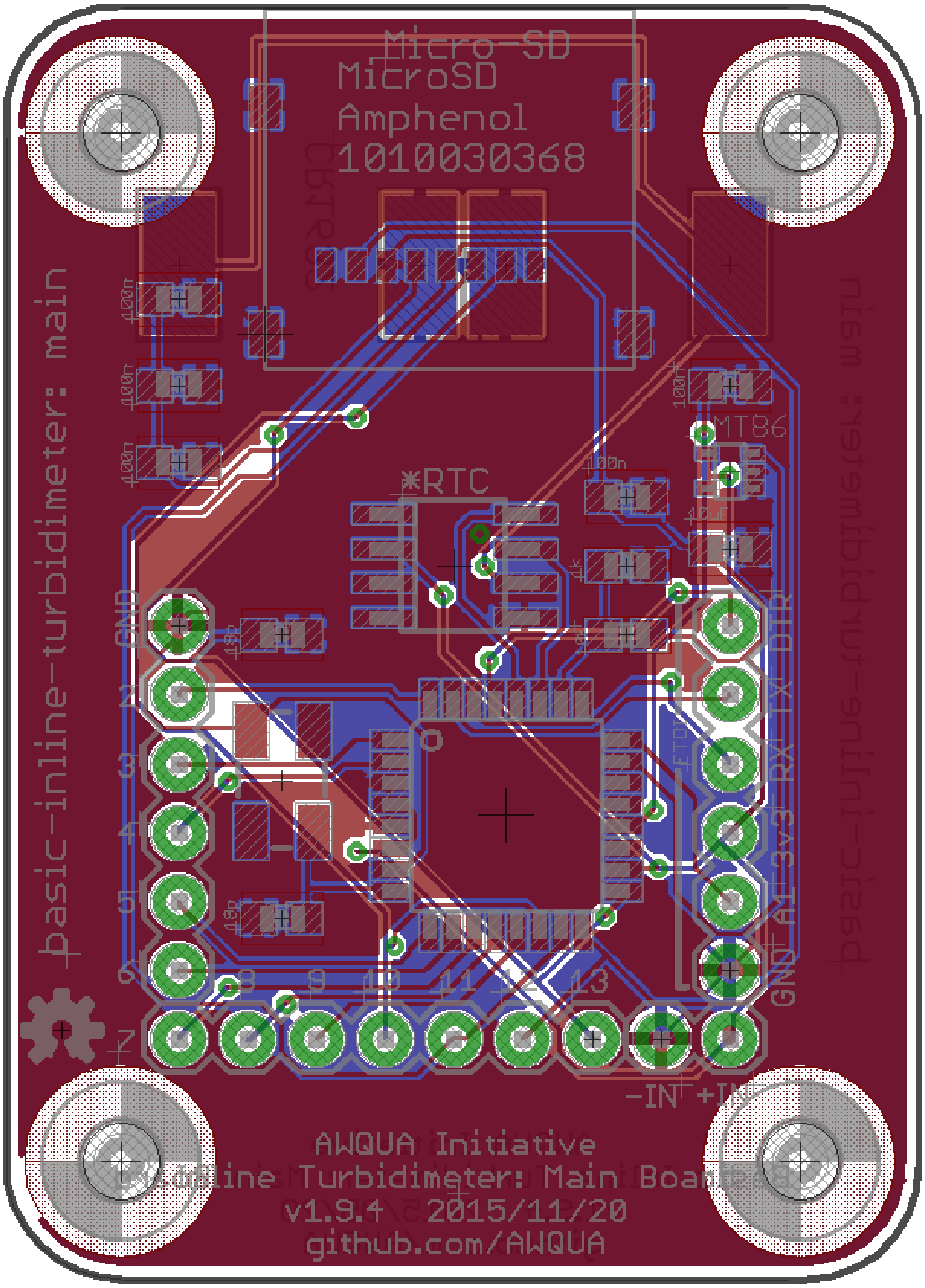
B.1.2 Electronic schematics and wiring

The microprocessor and connected components of the open-source turbidimeter are depicted below in EagleCAD formats (Figure A.2).

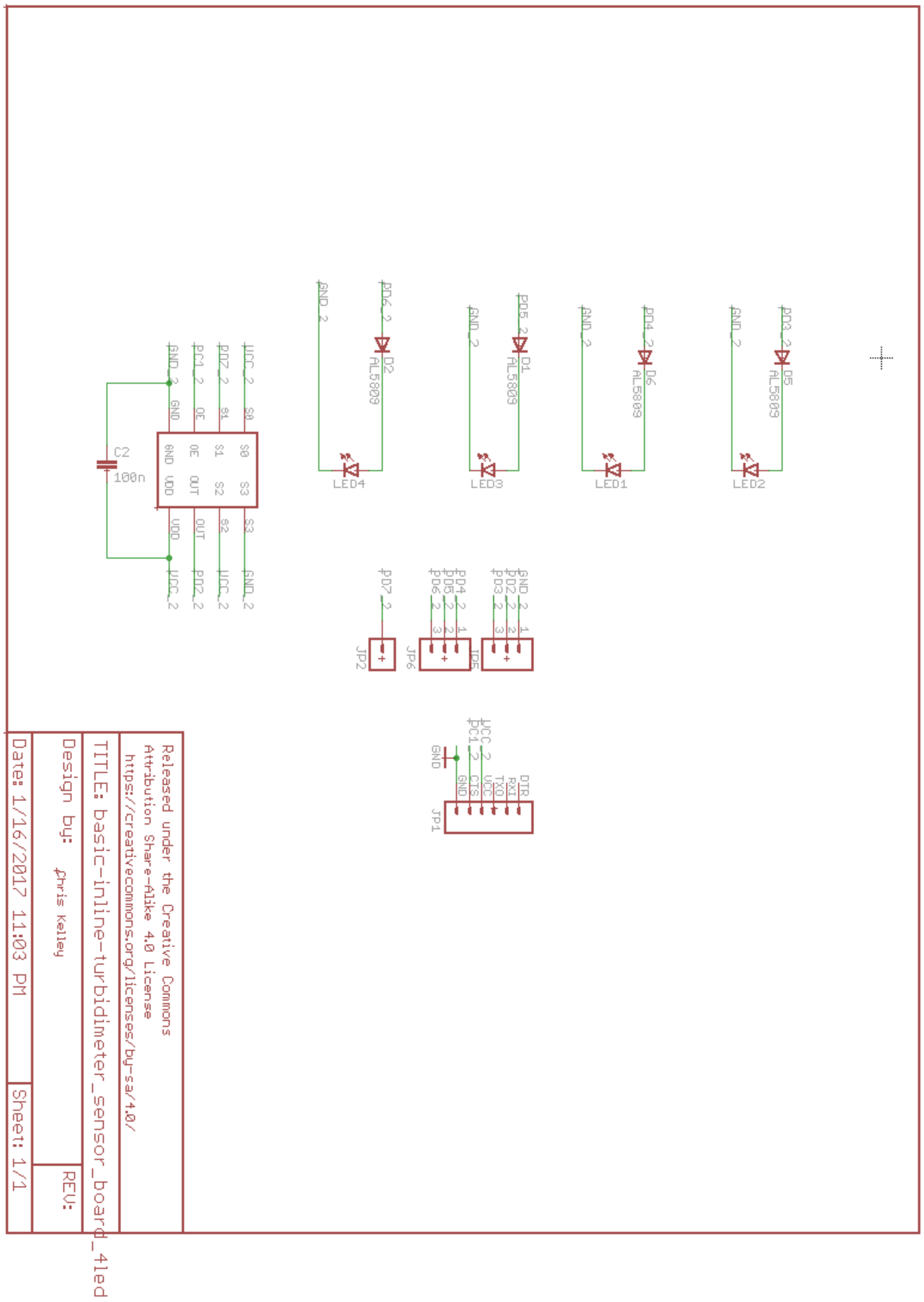
Figure B.2. Circuit boards of the Monocle Inline Turbidimeter, presented in Eagle schematic and board layouts.



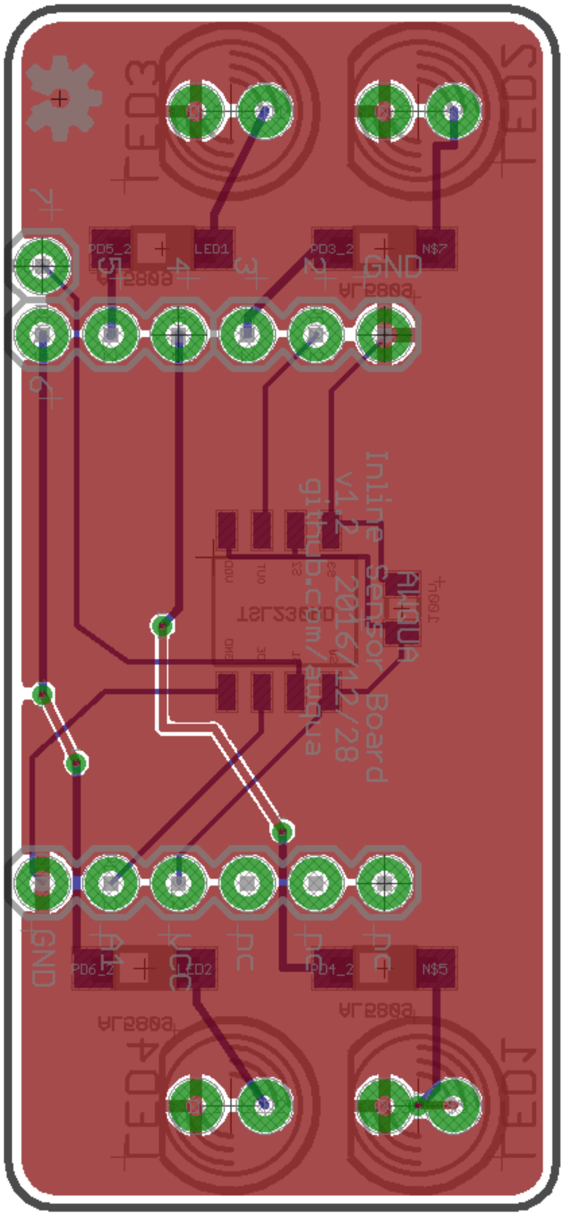
(a) Main board, schematic layout



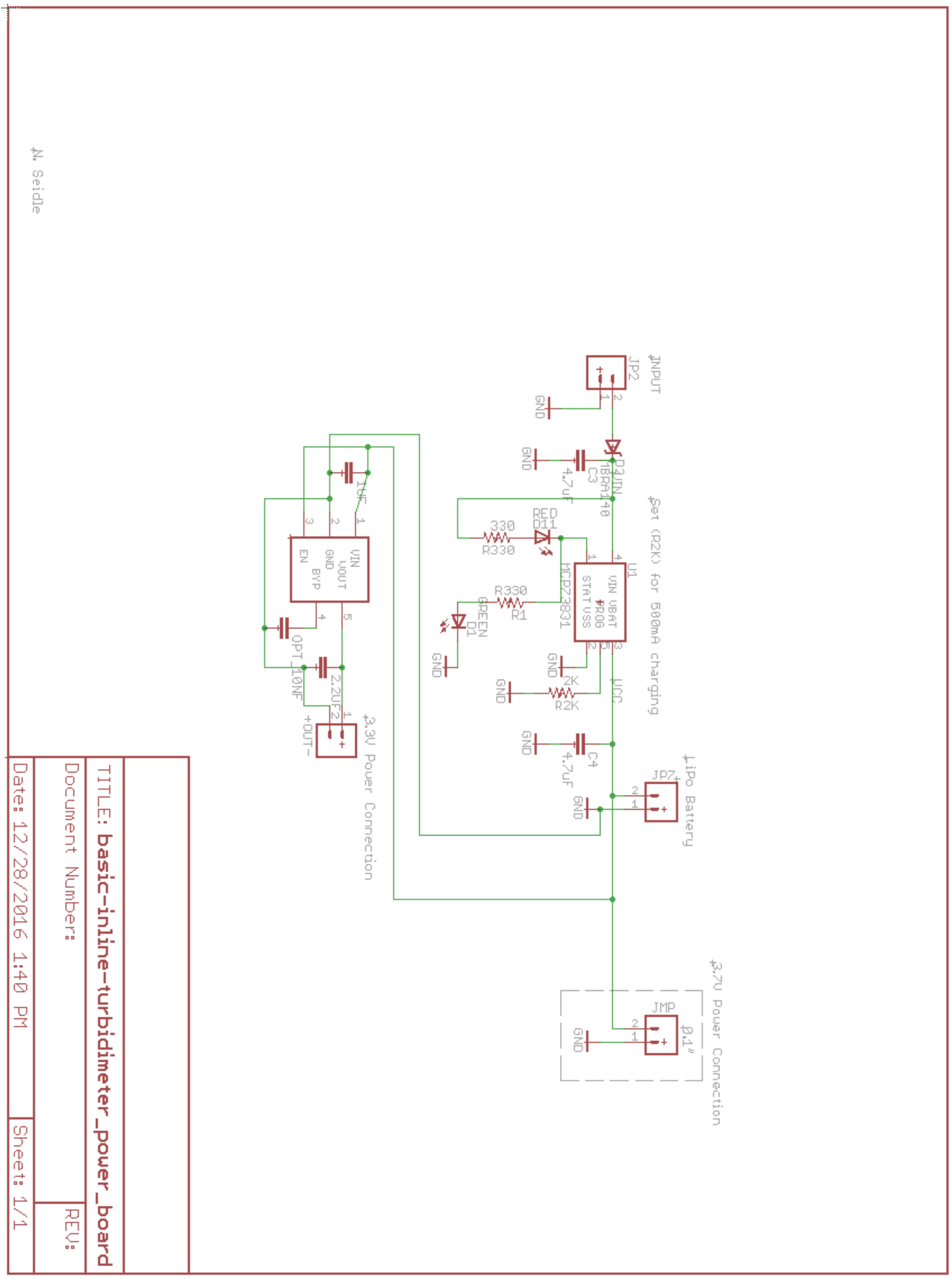
(b) Main board, board layout



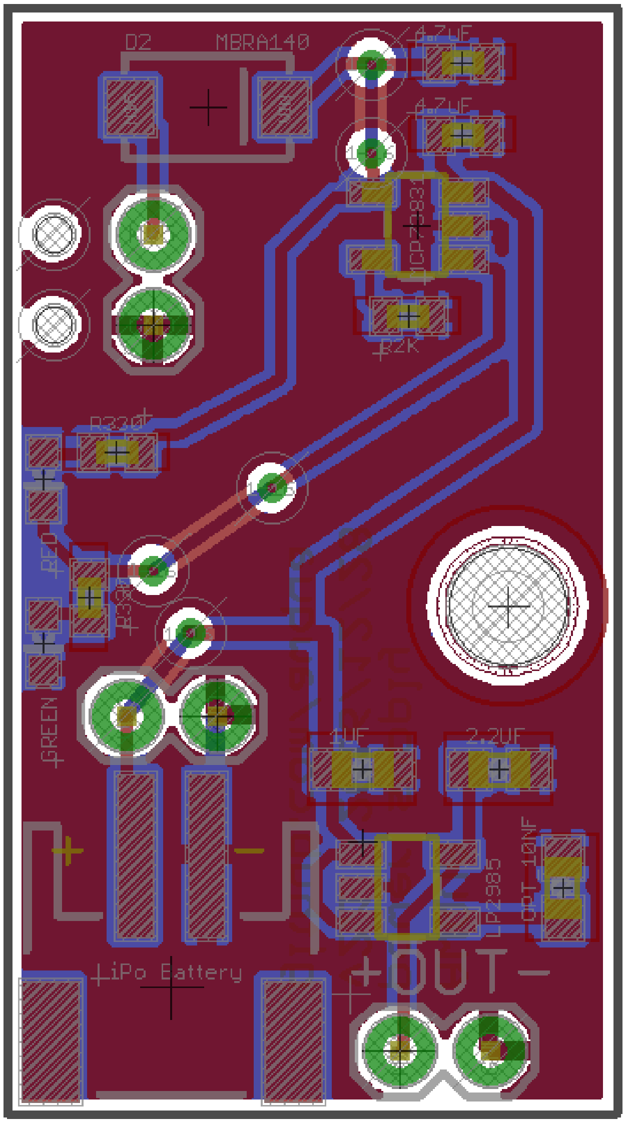
(c) TSL230R light-to-frequency sensor and LED board, schematic layout



(d) TSL230R light-to-frequency sensor with four IR LEDs, board layout



(e) Power board, schematic layout



(f) Power board, board layout

B.1.3 Firmware

```
/*NB: To program an Monocle inline turbidimeter, upload this code. This is easily done in the Arduino IDE programming environment. Visit Arduino.org to learn more*/

//#include <SoftwareSerial.h>
#include <JeeLib.h>
#include <SPI.h>
```

```
#include <SD.h>
#include <Wire.h>

//#define NO_PORTA_PINCHANGES
//#define NO_PORTB_PINCHANGES
//#define NO_PORTC_PINCHANGES
#include <PinChangeInt.h>

#define BYTES_PER_FLOAT 4
#define LOOP_CYCLE  20000
#define SLEEP_CYCLE 4000
#define SERIAL_DELAY 100
#define READ_TM 500
#define BAUD_RATE 9600

#define SD_CS   10
#define LED1     5
#define LED2     6
#define LED3     8
#define LED4     9
#define TPIN     A0
#define TSL_OE   A1    // frequency signal from the sensor
#define VPIN     A3
#define TSL_S0    2
#define TSL_S1    3
#define TSL_FREQ  4    // frequency signal from the sensor
#define DIV_R1 10000
#define DIV_R2  1000
```

```
#define VDIVIDER 11    // R2 / (R1 + R2)
#define SCALE 2

#define SERIAL_DEBUG true
#define RTC_DEBUG false
#define DEBUG_CHECK_CARD_AT_STARTUP false

//SENSING WINDOW VARIABLES
//1/7, 1/5, 1/3, 2/11, 6/13, 5/17, 1/19, 15/23
float window_stretch[] = {.142857, .2, .333333, .1818182, .461538, .294117, .0526316, .652174};
int WINDOW_STRETCH_COUNT = sizeof(window_stretch) / BYTES_PER_FLOAT;

//BOARD VARIABLES
File myFile;
boolean logfile_error = false;
unsigned long pulse_count;
long idx = 0;

//Jeelib boilerplate function for Sleepy calls
ISR(WDT_vect) { Sleepy::watchdogEvent(); }

void setup() {
  analogReference(INTERNAL);
  //set up downtime indicator LED
  pinMode(9, OUTPUT);
  pinMode(A2, INPUT);

  //set up sensor and IR LEDs
```

```
  pinMode(TPIN, INPUT);
  pinMode(LED1, OUTPUT);
  pinMode(LED2, OUTPUT);
  pinMode(LED3, OUTPUT);
  pinMode(LED4, OUTPUT);
  pinMode(TSL_FREQ, INPUT);
  pinMode(TSL_S0, OUTPUT);
  pinMode(TSL_S1, OUTPUT);
  pinMode(TSL_OE, OUTPUT);
  digitalWrite(TSL_OE, LOW);
  digitalWrite(TSL_S0, HIGH);
  digitalWrite(TSL_S1, HIGH);

  //set up RTC and Serial
  Wire.begin();

  if(SERIAL_DEBUG){
    Serial.begin(BAUD_RATE);
    Serial.println(F("starting..."));
    //Serial.end();
  }

  // clear /EOSC bit // Sometimes necessary to ensure that the clock  // keeps running on just battery power.
Once set, it shouldn't need to be reset but it's a good  // idea to make sure.
  Wire.beginTransmission(0x68); // address DS3231
  Wire.write(0x0E); // select register
  Wire.write(0b00011100); // write register bitmap, bit 7 is /EOSC
  Wire.endTransmission();
```

```
  if(RTC_DEBUG){ set_rtc_time(byte(00), byte(45), byte(13), byte(6), byte(3), byte(6), byte(16)); delay(100);}
  char out_ts[22];
  get_rtc_time(out_ts);

  //setup SD card
  pinMode(SD_CS, OUTPUT);
  if (!SD.begin(SD_CS)) {
    logfile_error = true;
    if(SERIAL_DEBUG){Serial.println(F("initialization failed!"));}
  }
  else{
    if(SERIAL_DEBUG){Serial.println(F("initialization done."));}
  }
    // re-open the file for reading:
  myFile = SD.open("log.txt");
  if (myFile){
    if(SERIAL_DEBUG && DEBUG_CHECK_CARD_AT_STARTUP) {
      Serial.println(F("log.txt:"));
      while (myFile.available()) {Serial.write(myFile.read());}
      myFile.close();
    }
  }else{
    if(SERIAL_DEBUG){Serial.println(F("error opening log.txt"));}
    logfile_error = true;
  }
  myFile.close();
```

```
  if(SERIAL_DEBUG){
    Serial.println(F("waiting..."));
    delay(5000);
    Serial.println(F("done waiting..."));
  }
}

void add_pulse() {++pulse_count;} //ISR function for sensor

void loop(){
  long loop_timer = millis();
  Serial.print(F("loop start timer: "));
  Serial.println(loop_timer);
  float v = getVoltageLevel();
  Serial.print("voltage: ");
  Serial.println(v);
  if(v > 2.95){
    char rd_idx[7];
    char out_ts[22];
    char out_data[12];
    get_rtc_time(out_ts);
    sprintf (rd_idx, "%lu", idx);
    take_readings(6, true, false, false);
    float reading = take_readings(14, false, true, true);
    dtostrf(reading,3,3,out_data);
    myFile = SD.open("log.txt", FILE_WRITE);
    if (myFile) {
```

```
    float t = read_temperature();
    if(SERIAL_DEBUG){
      Serial.print(F("writing to logfile\t"));
      Serial.print(t);
      Serial.print(F(","));
      Serial.print(v);
      Serial.print(F(","));
      Serial.print(out_ts);
      Serial.print(F(","));
      Serial.println(out_data);
    }
    myFile.print(rd_idx);
    myFile.print(F(","));
    myFile.print(t);
    myFile.print(F(","));
    myFile.print(v);
    myFile.print(F(","));
    myFile.print(out_ts);
    myFile.print(F(","));
    myFile.println(out_data);
    myFile.close();
    logfile_error = false;
  } else {
    logfile_error = true;
  }
  idx++;
}
```

```
if(SERIAL_DEBUG){
  Serial.println(F("preparing to sleep now..."));
  Serial.print(F("millis: "));
  Serial.println(millis());
  delay(SERIAL_DELAY);
  Serial.end();
}
digitalWrite(TSL_OE, HIGH);
//SIM900power();
while(millis() - loop_timer < LOOP_CYCLE - SERIAL_DELAY){
  long time_elapsed = millis() - loop_timer;
  if(LOOP_CYCLE - time_elapsed > SLEEP_CYCLE){
    Sleepy::loseSomeTime(SLEEP_CYCLE);
    //delay(SLEEP_CYCLE);
  }
  else{
    Sleepy::loseSomeTime(LOOP_CYCLE - time_elapsed - SERIAL_DELAY);
  }
}

if(SERIAL_DEBUG){
  Serial.begin(BAUD_RATE);
}
delay(SERIAL_DELAY);
if(SERIAL_DEBUG){
  Serial.println(F("waking up now..."));
}
digitalWrite(TSL_OE, LOW);
```

```
 //SIM900power();
}

/******************************************************************/
float getVoltageLevel(){
 float v = analogRead(VPIN); //drop the first reading
 delay(100);
 v = float(analogRead(VPIN));
 if(SERIAL_DEBUG){
  Serial.print(F("raw voltage divider value: "));
  Serial.println(v);
 }
 //float divider_value = float(DIV_R2) / float(DIV_R1+DIV_R2);
 return v / 1023.0 * 1.1 * VDIVIDER;
 //return system_voltage;
}

float read_temperature(){
 float tsum = 0.0;
 analogReference(DEFAULT);
 delay(5);
 int t = analogRead(TPIN);
 delay(10);
 for(int i = 0; i < 16; i++){//oversampling to smooth signal and hopefully raise precision by two bits
  tsum += analogRead(TPIN);
  delay(10);
 }
 tsum /=16;
```

```
  if(SERIAL_DEBUG){
    Serial.print(F("oversampled raw temperature value: "));
    Serial.println(tsum);
  }
  analogReference(INTERNAL);
  delay(5);
  return tsum;
}

float take_readings(int rdgs, boolean throwaway, boolean dark_counts, boolean stretched){
  float STRETCH = 0.0;
  PCintPort::attachInterrupt(TSL_FREQ, add_pulse, RISING);
  delay(5);
  float rd = 0.0, high = 0.0, low = 1000000.0, sum = 0.0, avg = 0.0;
  long read_timer = 0;
  for(int i = 0; i < rdgs; ++i){
    rd = 0.0;
    if(dark_counts){
      digitalWrite(LED1, LOW);
      digitalWrite(LED2, LOW);
      digitalWrite(LED3, LOW);
      digitalWrite(LED4, LOW);
      delay(2);
      read_timer = millis();
      pulse_count = 0;
      while (read_timer + READ_TM > millis()){;}
      rd -= pulse_count / SCALE;
    }
```

```
  digitalWrite(LED1, HIGH);
  digitalWrite(LED2, HIGH);
  digitalWrite(LED3, HIGH);
  digitalWrite(LED4, HIGH);
  delay(2);
  if(stretched){
    STRETCH = window_stretch[i % WINDOW_STRETCH_COUNT]; //Serial.print(F("stretch index: "));
  }
  read_timer = millis();
  pulse_count = 0;
  while (read_timer + READ_TM * (1+STRETCH) > millis()){;}
  rd += pulse_count / SCALE / (1+STRETCH);
  if(rd > high){ high = rd;}
  if(rd < low){low = rd;}
  sum += rd;
  if(SERIAL_DEBUG && !throwaway){
    Serial.print(F("reading: "));
    Serial.println(rd);
  }
}
digitalWrite(LED1, LOW);
digitalWrite(LED2, LOW);
avg = 0.0;
if(rdgs > 2){
  sum -= high + low;
  avg = sum / (rdgs - 2);
}else{
  avg = sum / rdgs;
```

```
  }
  detachInterrupt(TSL_FREQ);
  delay(5);
  if(SERIAL_DEBUG && !throwaway){
    Serial.print(F("average: "));
    Serial.println(avg);
    Serial.println();
    delay(100);
  }
  return avg;
}


void get_rtc_time(char *buffer){
  // send request to receive data starting at register 0
  Wire.beginTransmission(0x68);     // 0x68 is DS3231 device address
  Wire.write((byte)0);              // start at register 0
  Wire.endTransmission();
  Wire.requestFrom(0x68, 7);        // request info
  while(Wire.available())  {
    int seconds = Wire.read();      // get seconds
    int minutes = Wire.read();      // get minutes
    int hours = bcdToDec(Wire.read() & 0b111111);   // get hours
    int dotw = bcdToDec(Wire.read());
    int dotm = bcdToDec(Wire.read());
    int mnth = bcdToDec(Wire.read());
    int yr = bcdToDec(Wire.read());
    seconds = (((seconds & 0b11110000)>>4)*10 + (seconds & 0b00001111)); // convert BCD to decimal
    minutes = (((minutes & 0b11110000)>>4)*10 + (minutes & 0b00001111)); // convert BCD to decimal
```

```
    yr += 2000;   //need to fix this in the next 84 years...
    if(seconds >= 10 && minutes >= 10){sprintf(buffer, "%d/%d/%d %d:%d:%d", mnth, dotm, yr, hours, minutes, seconds);}
    if(seconds >= 10 && minutes < 10){sprintf(buffer, "%d/%d/%d %d:0%d:%d", mnth, dotm, yr, hours, minutes, seconds);}
    if(seconds < 10 && minutes < 10){sprintf(buffer, "%d/%d/%d %d:0%d:0%d", mnth, dotm, yr, hours, minutes, seconds);}
    if(seconds < 10 && minutes >= 10){sprintf(buffer, "%d/%d/%d %d:%d:0%d", mnth, dotm, yr, hours, minutes, seconds);}
  }
}


//set the time on the DS3231M
void set_rtc_time(byte seconds, byte minutes, byte hours, byte dotw, byte dotm, byte mnth, byte yr){  // sets time and date data to DS3231
  Wire.beginTransmission(0x68);
  Wire.write(0);                  // set next input to start at the seconds register
  Wire.write(decToBcd(seconds));  // set seconds
  Wire.write(decToBcd(minutes));  // set minutes
  Wire.write(decToBcd(hours));    // set hours
  Wire.write(decToBcd(dotm));     // set day of week (1=Sunday, 7=Saturday)
  Wire.write(decToBcd(dotm));     // set date (1 to 31)
  Wire.write(decToBcd(mnth));     // set month
  Wire.write(decToBcd(yr));       // set year (0 to 99)
  Wire.endTransmission();
}


// Convert binary coded decimal to normal decimal
```

```
byte bcdToDec(byte val) {return ( (val/16*10) + (val%16) );}


//opposite of bcdToDec
byte decToBcd(byte val) {return( (val/10*16) + (val%10) );}
```

B.1.4 Structural components

The case for the Monocle inline turbidimeter is composed of a SERPAC 111-BLACK (see https://octopart.com/search?q=111-BLACK+SERPAC) which is made waterproof with the use of a matching rubber gasket (https://octopart.com/search?q=serpac%20ps-11&start=0). A square opening measuring roughly one inch by two inches is cut into the center of the top face of the case, and a piece of 2mm- or 3mm-thick clear acrylic (clearly bigger than the cut) is epoxied over the hole.

B.1.5 Tools required

To prepare the case, a rotary hand tool such as those made by Dremel (Racine, WI, USA) would be useful. Waterproof epoxy (such as boat epoxy) is suitable for attaching the acrylic viewport. A solder paste syringe, tweezers, an electric skillet, a toothbrush, and 70% isopropyl rubbing alcohol are needed for constructing the circuit boards. An electric fan is recommended if the work area does not have high ventilation.

B.1.6 Assembly

Case: Cut a one-inch by two-inch viewport on the top side of the case, and a three-inch by two-inch piece of clear acrylic. Sand the cut face of the case and the outer edge of the acrylic piece, and epoxy together. This process takes roughly fifteen minutes, though the epoxy will need to sit for one day to cure.

PCB: For circuit board assembly, refer first to Section A.2.1.6 for general guidance. The circuit boards have been successfully assembled for prototypes using only a solder syringe and tweezers for the surface-mount components (cooking the board in a typical covered electric skillet), and a soldering iron for the through-hole components. Solder the sensor board to the main board, matching the parallel rows of pins on the sensor board to the parallel rows of pins on the main board (with the sensor on the sensor board facing away from the main board). Fit a square-inch section of visible light filter (such as exposed photographic film) and fit it over the sensor (secure with tape, glue, or wedging under the four LEDs). The circuit board soldering and assembly is estimated to take roughly 45 minutes.

Connect the LiPo battery to the JST connector on the power board, then connect the positive and negative terminals of the main board and power board (labeled +IN- and +OUT-, respectively) with two-inch lengths of jacketed 22-gage copper wire. Connect the receiving coil and board of the inductive charging set to the input of the power board with one-inch lengths of 22-gage copper wire. Attach the main/sensor board combo to the internal guideposts of the cut half of the case (securing the main board to the case with screws or epoxy). A small length of Kapton tape can be used to affix the inductive charging coil to the back center of the back half of the case. A small section of foam insulation (at least ¼” thick) should be used to separate the inductive charging coil from the LiPo battery. A piece double-sided foam tape may also be helpful to hold larger components like the insulation and battery in place inside the case.

Once all of the electrical components have been secured inside the device, the case halves can be closed around the waterproofing rubber gasket, and connected together with the screws that come with the case. Altogether, it is estimated to take roughly 75 minutes to assemble one Monocle by hand.

B.1.7 Bill of Fabrication

In addition to the cost of components outlined Bill of Materials given in Table B.1, the cost of the tools required to produce the Monocle deserve attention and documentation. Table B.2 outlines the basic tools and supplies necessary for construction of a Monocle and their estimated price (in the United States). All of these expenses, except for labor, may be spread among multiple Monocles if a factory is being established. The consumables in Table B.2 – solder paste, boat epoxy, and rubbing alcohol – can be used to produce dozens of Monocle devices in the quantities quoted.

Table B.2. Bill of Fabrication for the Monocle inline turbidimeter.

Expense	Purpose	Estimated price (US$)
Electric skillet	SMD soldering	50
Solder paste	SMD soldering	20
Tweezers, right-angle	placing components	4
Utility knife	stencil trimming	5
3-mil Mylar sheet	solder mask	5
Boat epoxy	sealing case	6
Snippers	trimming wires	2
Screwdriver	sealing case	2
Isopropyl alcohol	cleaning PCBs	2
Toothbrush	cleaning PCBs	1
Rotary hand tool	cutting viewport	100
Face mask	safety	5
Safety goggles	safety	5
Labor (1.25hr @$20/hr)	assembly	25
	Total:	**232**

B.2 User guide for the Monocle inline turbidimeter

B.2.1 Introduction

This document lists the commands recognized by versions 2.0 and 2.1 of the AWQUA Inline Turbidimeter. This device is hermetically sealed for waterproofing, but can communicate wirelessly using the Bluetooth v2.1 protocol.

Applicable hardware versions: 2.0, 2.1

This information last updated: 2017-05-01

B.2.2 Establishing Connection

To turn on the AWQUA Inline Turbidimeter's Bluetooth capabilities, simply place the device onto its inductive charging station. Please wait 5-10 seconds for the device to complete any ongoing operations, then open a serial terminal in an Android phone or Bluetooth-capable Linux or Windows computer (an Apple computer may work, but an iPhone will not). Connect to the Bluetooth address given in the documentation for your AWQUA Inline Turbidimeter with the following connection settings:

9600 baud, 8 data bits, 1 stop bit, no parity bit

The Bluetooth pin should be '1234' (or possibly '1111'). You should only need to enter the pin when pairing with a device for the first time.

Once paired and connected, you should receive a confirmation message from the turbidimeter that it is connected and ready to receive commands.

B.2.3 Command List

NOTE: all valid commands must end either with a non-printing carriage return ['\r'], or with the 'x' character

Single-character commands:

b: Force Bluetooth off immediately.

B: Force Bluetooth to stay on even when disconnected from charger. Please note that this is not recommended for the 2.0 version of the AWQUA Inline Turbidimeter due to hardware constraints.

c: Check calibration constants. For a detailed explanation of these constants, see the description of the 'C' command below.

D: Echo and then delete contents of on-board memory. Please note that this cannot be undone.

f: Take a dummy reading immediately, to verify operational status. Due to hardware constraints, in the 2.0 version of the AWQUA Inline Turbidimeter the temperature data in these dummy readings are not reliable.

i: Check the interval between readings, given in seconds.

l (Lower-case L): Check which of the four LEDs is currently set to turn on for each reading.

m: Echo contents of on-board memory.

r: Check the number of replicate measurements taken per reading.

S: Put the device into deep-sleep mode. When this command is executed, the device will wait six seconds before settling into its lowest-power mode; please remove the device from the charging station during this station. The device will stay in deep sleep until it is once again placed on the charging station.

t: Check the timestamp of the on-board clock.

v: Check the system voltage.

w: Check the sampling window of each measurement, given in milliseconds.

Multi-character commands:

i: Set the interval between readings, in seconds (default 601). The syntax for this command is "ixxxx" where the xxxx is a number, two to four digits in length, representing the number of seconds in between readings. Please note that this is limited to a minimum of 30 seconds (i30) and a maximum of 7200 seconds (i7200).

Special note for v2.0: Due to how lowest-power mode is implemented in v2.0 of the AWQUA Inline Turbidimeter, the microprocessor's internal clock will tend to run slightly slow during deep sleep. Please note that this does NOT affect the accuracy of the real-time clock used for time-stamping. For best results, add one second for every ten minutes in the interval time (e.g. 601s for a ten-minute interval, 1202s for a twenty-minute interval, etc.).

L: Set which LEDs will turn on for each reading. The syntax for this command if "Lxxxx" where each x is either a 1 or 0 and represents whether the corresponding LED will be turned on during sampling.

r: Set the number of replicate measurements taken during each reading (default 8). The syntax for this command is "rx" where the x is a single-digit number representing the number of replicate measurements taken each reading. Please note that this is limited to a minimum of 3 replicates (r3) and a maximum of 10 replicates (r0).

w: Set the sampling window of each measurement, in milliseconds (default 500). The syntax for this command is "wxxxx" where the xxxx is a number, three to four digits in length, representing the timespan of each replicate measurement taken during each reading. Please note that this is limited to a minimum of 200 milliseconds (w200) and a maximum of 1000 milliseconds (w1000).

Multi-part commands:

C: Set the calibration constants. These are used to convert the raw sensor signal into a turbidity (NTU) value. There are sixteen calibration constants, and each one is set in two halves with this command. Since the 8-bit microprocessor of the AWQUA Inline Turbidimeter v2.x does not have the memory space sufficient for the polynomial regression required to establish its own calibration constants, this function was added to the API to assist in recalibration efforts. (Please note that an Android app to help automate this process is being developed.)

The syntax for this command is “C[a-p][H,L][x+]z”, which means:

> ‘C’ initiates the command.
>
> ‘[a-p]’, the “place index”, represents a single character of the alphabet between ‘a’ and ‘p’ (inclusive), which in turn maps to a numerical address from 0 (‘a’) to 15 (‘p’). This numerical address represents the position of the calibration constant in an array in the device’s non-volatile EEPROM memory. (See “Rationale”, below.)
>
> ‘[H,L]’, the “side index”, is must be either ‘H’ or ‘L’ and indicates whether the integer part or the decimal part, respectively, of the calibration constant referenced by the place index is being edited.
>
> ‘[x+]’, the data point, is a one- to nine-digit integer, which represents the value being written to the indicated “side” of the indicated calibration constant.
>
> ‘z’ terminates and executes the command.

<u>Rationale:</u> The AWQUA Inline Turbidimeter calibration logic allows for up to three cubic regressions that cover the span of the measurement range of interest (which is typically 0-1000 NTU or 0-2000 NTU). These cubic curves are represented by cutoff points [y0 – y3] and polynomial coefficients [(a0,b0,c0,d0) – (a2,b2,c2,d2)], which correspond thusly to the place index:

0: y0, 1: y1, 2: y2, 3: y3

4: a0, 5: b0, 6: c0, 7: d0

8: a1, 9: b1, 10: c1, 11: d1

12: a2, 13: b2, 14: c2, 15: d2

B.3 Supplementary calibration and validation data

B.3.1 Field testing data

The Monocle Inline Turbidimeter was tested in Kenya in late May 2017. As mentioned in Chapter 6, the ambient light rejection mechanisms of the Monocle device were insufficient to deal with the background light fluctuations encountered during testing. This resulted in, e.g., spurious (and physically impossible) negative Hertz readings from the light-to-frequency sensor. Roughly two days of raw testing data are summarized in Figure B.3 below. Field testing was additionally complicated by the very small number of grab samples taken with a commercial handheld turbidimeter for comparison with the Monocle. The five grab samples reported by the field testing partner are given in Figure B.4.

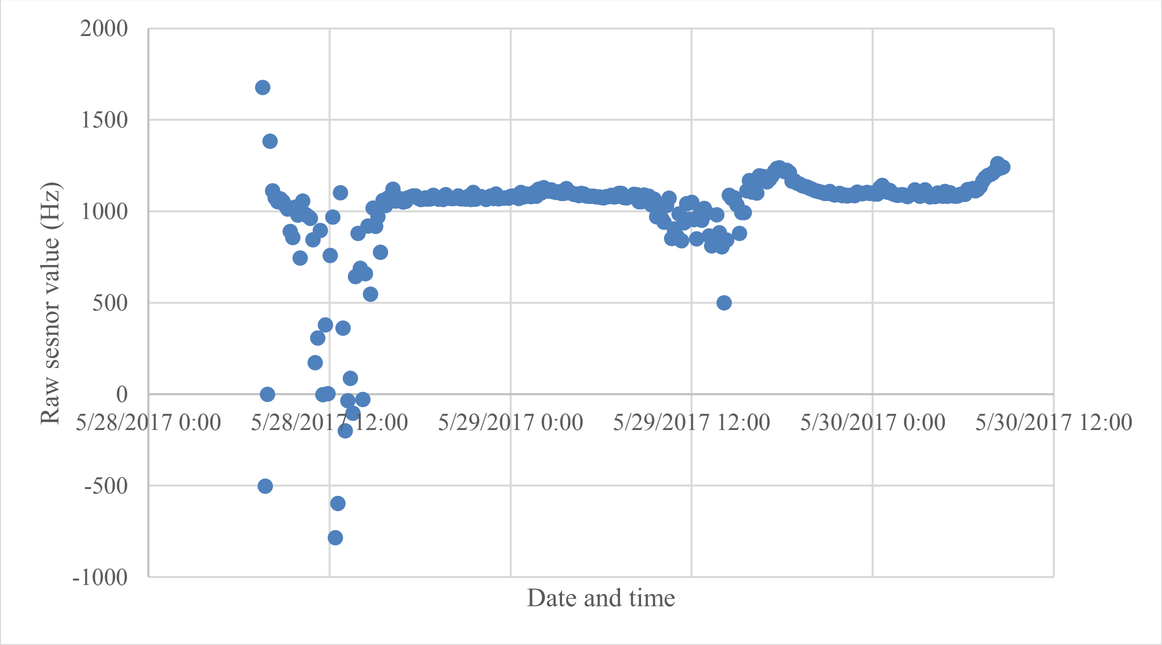


Figure B.3. Supplementary Monocle testing data from May 28th – 30th 2017, in a reach of the Sagana River in central Kenya.

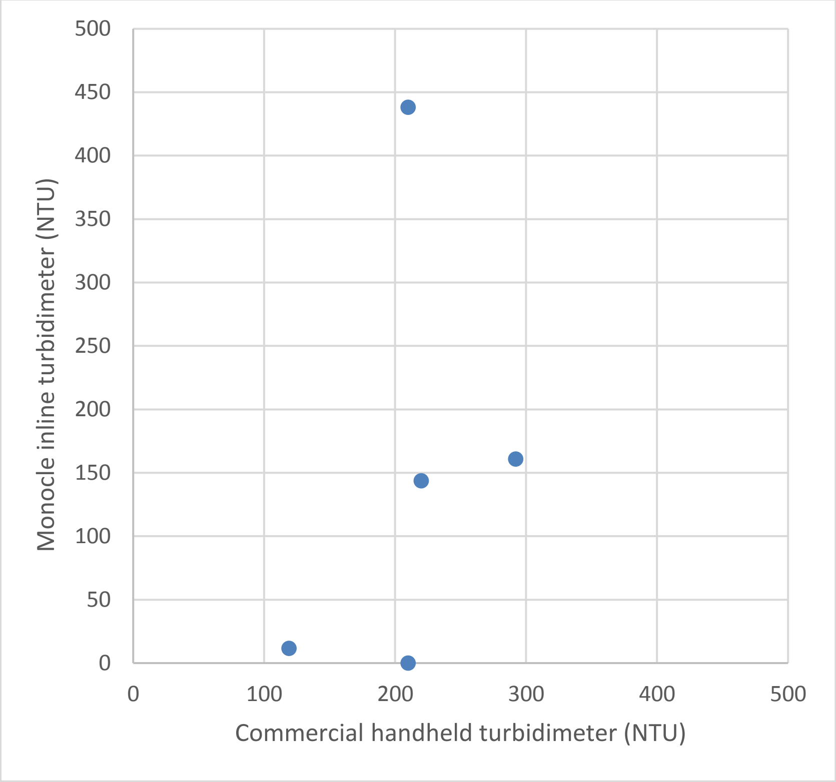


Figure B.4. Grab samples measured with a commercial handheld turbidimeter, and measurements taken with a Monocle inline turbidimeter, in a reach of the Sagana River in central Kenya during 28th – 30th May 2017.

B.3.2 Ease-of-use report

Dr. David Courtemanch, a freshwater science and policy specialist with the Maine Field Office of The Nature Conservancy, tested two Monocle prototypes in rivers in Kenya during the last week of May 2017. The following notes were sent by Dr. Courtemanch via email:

"The inductive coil doesn't seem to recharge the battery even after many hours (overnight) on the coil. Coil works fine for making the Bluetooth connection. Therefore I opened each unit several times to make direct connection (the unit seemed to hold its charge perfectly). This may have been how the wires separated in [Device #]02 or could have been in transit. The cases remained water tight even after opening several times but having to take the screws out too many times may eventually lead to failure. I think you told me that you are working on a sealed version."

"As noted, wires on [Device #]02 separated. You will need to give me instructions again where to re-solder these. I hope to set these out again in some streams in Maine for longer period to look at stability over time. Fouling did not seem to be a problem despite the high turbidity water in Sagana but I need to set these out longer to see if there is some long term effect. I don't see a problem that a basic lens cleaning protocol can't solve."

"The cases, while compact and perfect for use in our little streams, need to have some better means of attachment."

"Temperature readings consistent."

B.4 Field survey questions

Device ease of use

I found it easy to use the device today

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I was frustrated using the device today

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I was able to collect all the readings I needed

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

It was easy to recharge the device wirelessly

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

It was easy to transfer data from the device wirelessly

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree

(5) Strongly agree

Additional comments on device ease of use:

Device ergonomics

I was easily able to turn the device on and off

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I was easily able to see the charge and low-power indicator LEDs on the device

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

The device was easy to attach to where I needed to position it

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

Additional comments on device ergonomics:

User knowledge

I know how to use this device to measure turbidity

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I know how to wirelessly connect this device to a smartphone

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I have viewed a video tutorial for how to use this device

(1) Yes
(2) No

I know how to re-calibrate this device

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I have viewed a video tutorial for how to re-calibrate this device

(1) Yes
(2) No

I know how to check the temperature and voltage level of the device

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I know how to recharge this device

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

I know how to open this device

(1) Yes

(2) No

I know where I can get this device repaired

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

Additional comments about user knowledge:

Data collection form

Date	Time	Temperature	Voltage	Turbidity	Operator Name

I have completed the data collection form today

(1) Yes

(2) No

I found it easy to complete this form today

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

I was frustrated completing this form today

(1) Strongly disagree

(2) Disagree

(3) Neither agree nor disagree

(4) Agree

(5) Strongly agree

Additional comments about data collection form

Appendix C. Supplementary information for Chapter 7

C.1 Proposed Design of the Jar Opener

The Jar Opener is a proposed low-cost, open-source jar tester detailed in Chapter 7. A conceptual illustration of the Jar Opener is given in Figure C.1, with major subsystems color-coded. Note that the Figure is not drawn to scale and does not include all proposed features of the Jar Opener. The device is envisioned to be roughly 28 inches wide, 16 inches tall, and 12 inches deep.

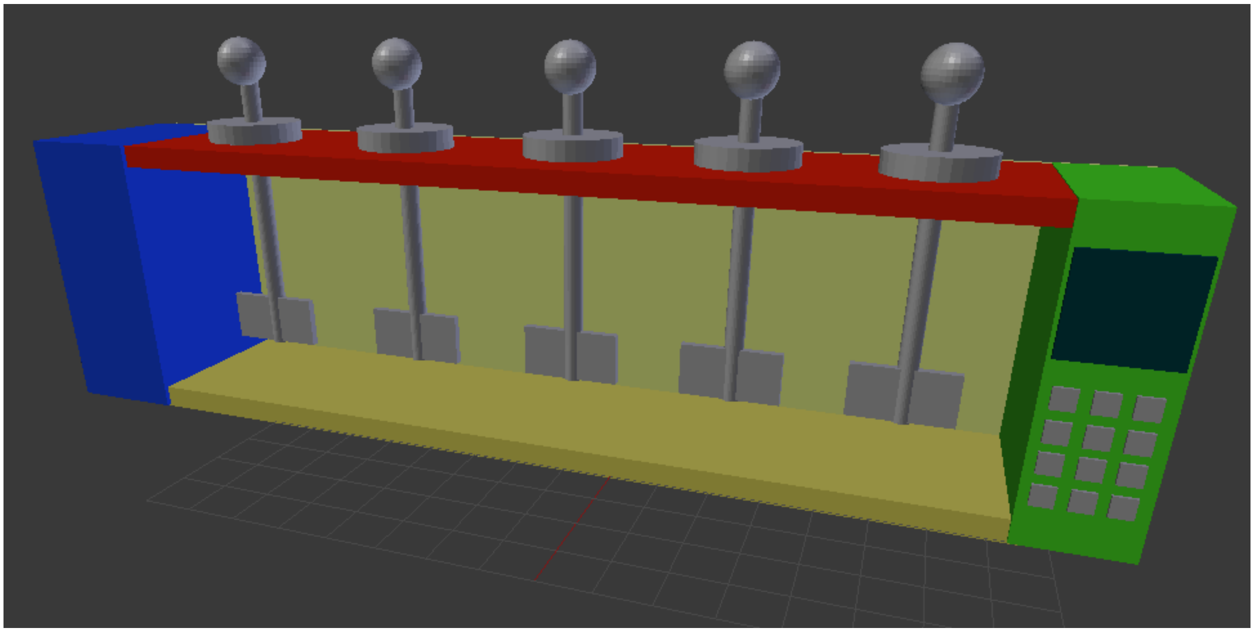


Figure C.1. Conceptual illustration of the Jar Opener with major subsystems color-coded: microprocessor and user interface (green), drive unit (blue), gearing (read), paddles (gray), supporting structure (yellow).

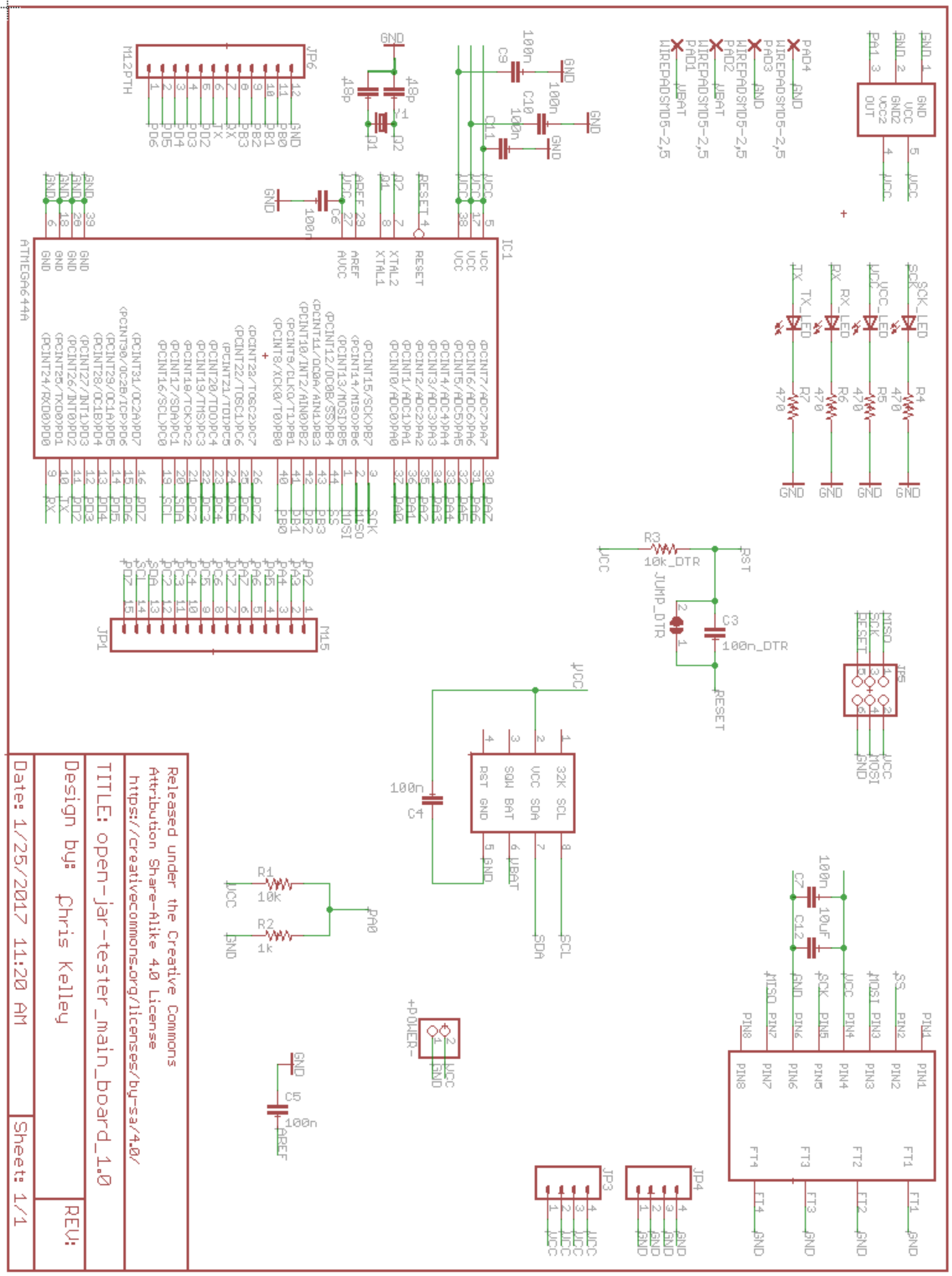
C.1.1 Bill of Materials

Table C.1. Bill of materials for the Jar Opener, showing description and cost estimate of each conceptual unit.

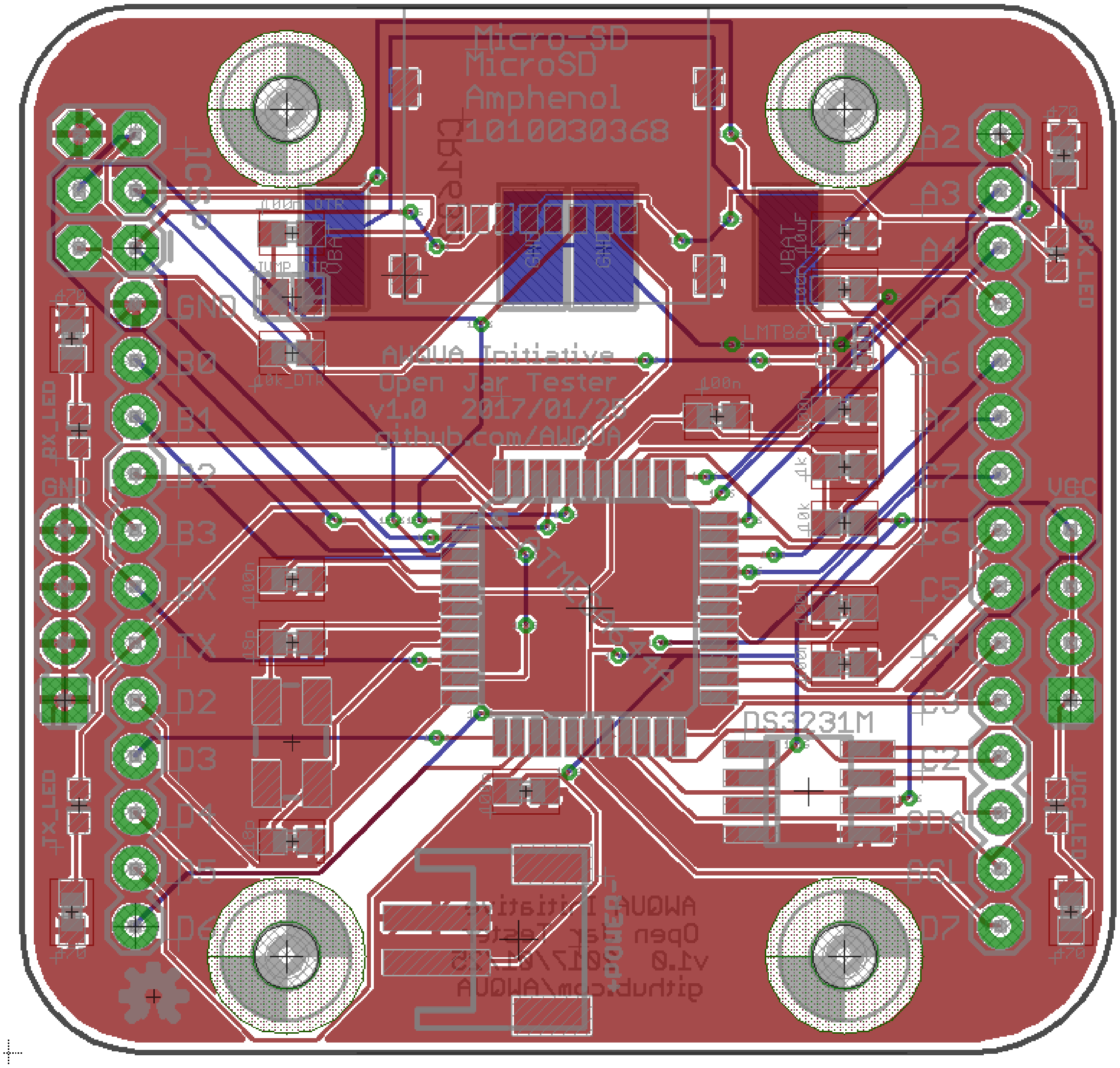
Name	Description	Cost Estimate ($)
frame	modified RepRap Mendel frame	20
casing	laser-cut black acrylic sheet	20
motor	12-24V windshield wiper motor	25
power	AC adapter, DC input, 12V regulator and 5V regulator	4
gearing	laser-cut black acrylic sheet	5
keypad	10-key waterproof keypad	5
microcontroller	ATMega644P microprocessor and support circuitry	7
beam break	Photo interrupter (such as Sharp GP1S59J0000F)	2
encoding wheel	laser-cut black acrylic sheet	2
shafts	3mm diam. carbon steel hex shaft, 1ft. X 5	8
paddles	steel plate, epoxied or spot-welded	2
jars	laser-cut clear acrylic sheet	15
communication	Internal Bluetooth unit	5
memory	removable MicroSD card, slot	4
atmospheric sensor	temperature, humidity, air pressure	7
buttons	Additional user controls (assume five)	3
screen	2.4" TFT LCD monitor	7
	Sum	**$141**

C.1.2 Electronic schematics and wiring

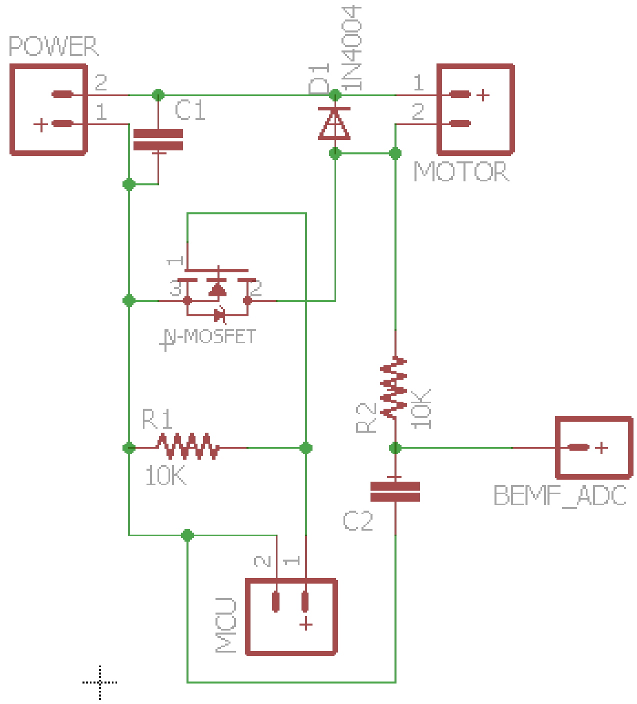
Figure C.1. Circuit boards of the Jar Opener, presented in Eagle schematic and board layouts.



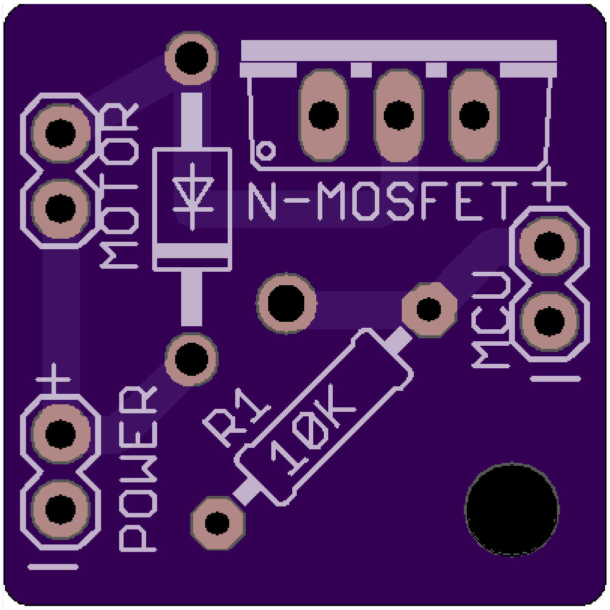
(a) Jar Opener main controller, schematic layout



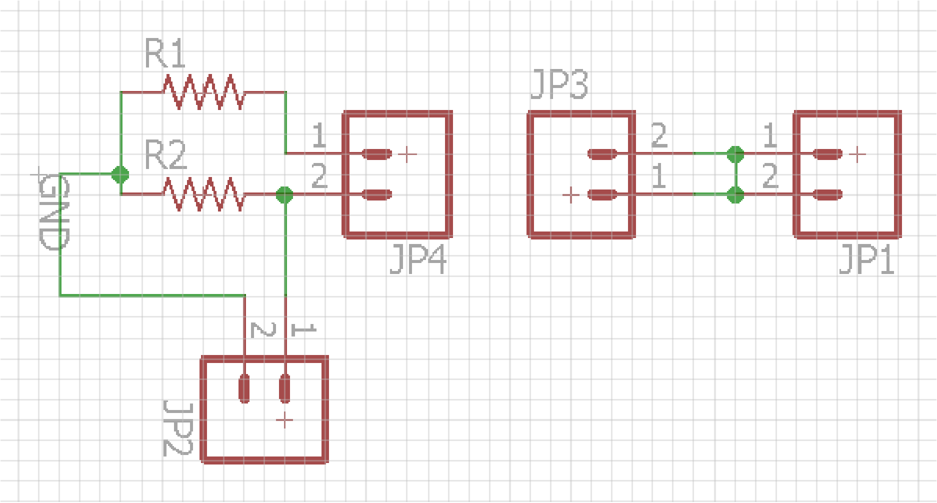
(b) Jar Opener main controller, board layout



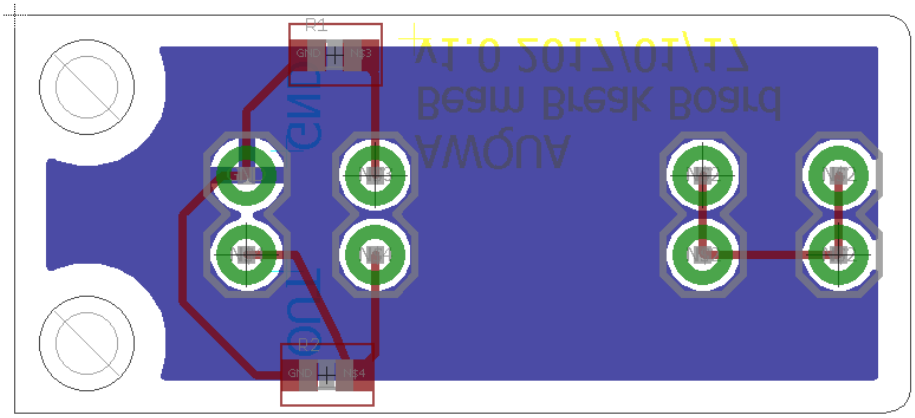
(a) Motor driver board, schematic layout



(b) Motor driver board, board layout



(c) Motor speed feedback circuit, schematic layout



(d) Motor speed feedback circuit, board layout

C.1.3 Firmware

```
/*

NOTE: The following test program is used to drive the windshield wiper motor that powers the Jar Opener prototype.   The basic serial interface handling provided can be used to evaluate the RPM of the motor at various PWM duty cycles (determined by the value of the OCR2B register compared to the maximum 255 value of the ATMega328 microprocessor’s internal 8-bit timer TIMER2). Switching frequency can also be adjusted by setting the clock pre-scaler bits CS20, CS21, and CS22 (see the ATMega328 datasheet for further details). For greater precision the internal 16-bit timer TIMER1 can be used, but this is reserved in the current design for a servo motor to drive the Open Jar Tester’s three-speed transmission.

*/

int serial_val = 0;

void setup() {

  Serial.begin(9600);

  pinMode(3, OUTPUT);

  pinMode(11, OUTPUT);
```

```
  TCCR2A = _BV(COM2A1) | _BV(COM2B1) | _BV(WGM21) | _BV(WGM20);

  TCCR2B = _BV(CS20);

  OCR2B = 127;

}

void loop() {

  while(Serial.available() > 0) {

    char new_byte = Serial.read();

    if (new_byte == -1) continue;

    else if (new_byte == '\n')

    {

      OCR2B = serial_val;

      Serial.println(serial_val % 255);

      serial_val = 0;

      break;

    }    else    {

      serial_val *= 10;

      serial_val += (new_byte - 48);

    }

  }

}
```

Appendix D. Cost of a common commercial handheld turbidimeter

To estimate the parts and labor costs to construct a basic commercial handheld turbidimeter, a "teardown" (disassembly with component identification) of a MicroTPI turbidimeter (HF Scientific, Fort Meyers, FL, USA) was conducted. The MicroTPI is a common, ISO 7027-certified turbidimeter, retailing in America for roughly $800 at the time of writing. The internal subsystems of the MicroTPI are shown in Figure D1. Parts were identified by their labels. Cost estimates are detailed in Table D1. Costs for major components were estimated through the electrical components price comparison website Octopart (https://octopart.com/); minor component (resistors, capacitors, inductors) prices were estimated in one lumped sum. The estimated parts and labor cost for the MicroTPI is $266.07 (see Table D.1).

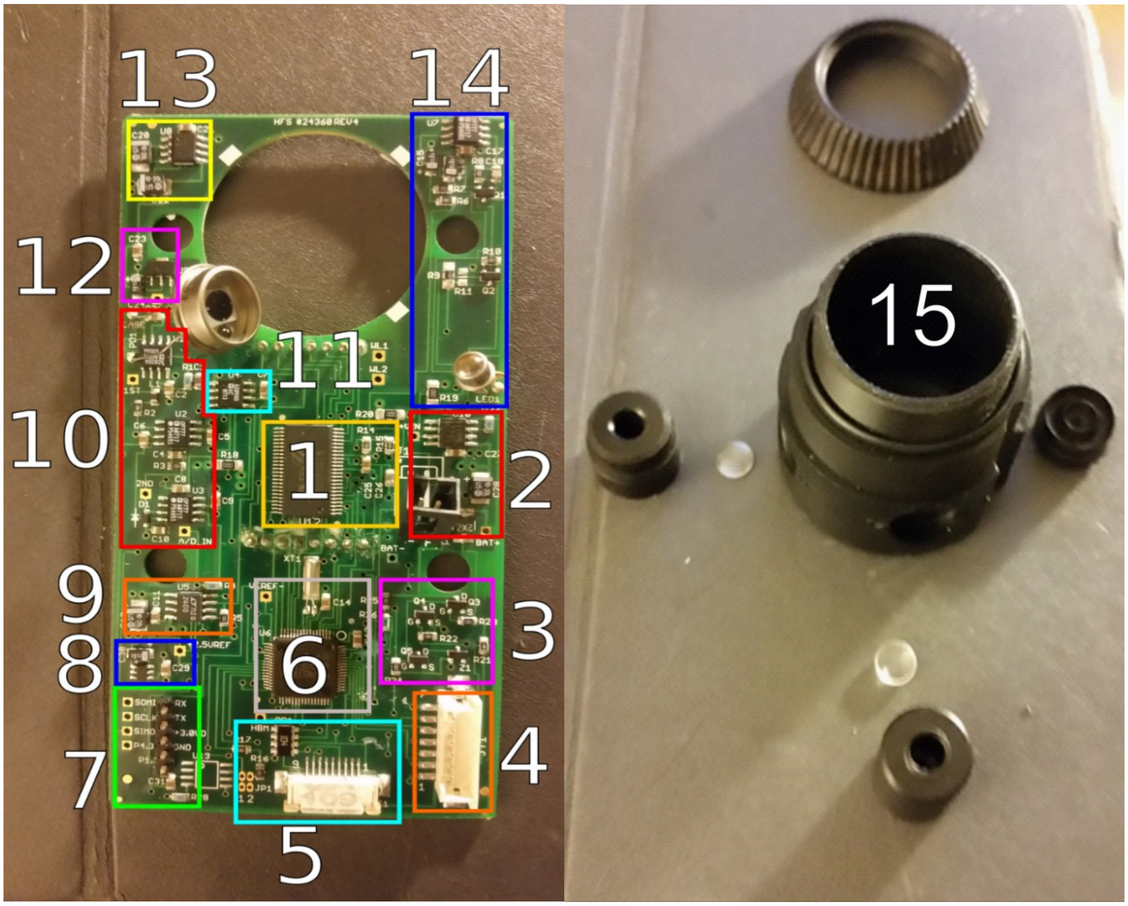


Figure D.1. Circuit board of an HF Scientific MicroTPI handheld turbidimeter, with subsystems identified: (1) display controller; (2) voltage regulator; (3) over-voltage and polarity; (4) device programming connector; (5) external keypad interface; (6) microprocessor; (7) serial debugging port; (8) precision voltage reference; (9) analog-to-digital converter; (10) photodiode with analog front-end; (11) digital potentiometer [purpose unclear]; (12) negative voltage regulator; (13) voltage inverter; (14) LED with brightness control; (15) multi-part cuvette holder, with snouts and lenses for the LED and photodiode, a small nub screwed in to the side of the cuvette chamber (not visible in Figure) to secure the cuvette in position by friction, and (presumably) a beam dump to reduce the amount of stray light hitting the photodiode.

Table D.1. Parts and labor costs (known and estimated, at the time of writing) for a MicroTPI handheld turbidimeter, assuming a manufactured quantity of 1000 devices.

PCB Subsystem	Part	Explanation	Cost each	Num.	Subtotal	Notes
10	AD820	Photodiode pre-amp	3.19	1	3.19	
10	OP777	Op amps	1.7	3	5.1	
11	AD8400	Digital potentiometer	2.08	1	2.08	
10	LTC2400	24-bit ADC	6.17	1	6.17	
6	MSP430F148	Microprocessor	5.46	1	5.46	
13	TC7662	Charge inverter	1.44	1	1.44	
13	ADP7182AUJZ	-3V regulator	1.82	1	1.82	A
2	TPS7330QD	3V regulator	1.67	1	1.67	
8	LT1790ACS6	2.5V reference	3.75	1	3.75	
1	HT1621B	Display controller	0.37	1	0.37	B
(multiple)	593D106X0020	10uF 20V capacitor	0.306	4	1.224	C
4	DF3DZ-7P	JTAG connector	0.48	1	0.48	
5	52271-2279	Controls connector	0.92	1	0.92	
	circuit board	PCB manufacture	1.37	1	1.37	
3, 14	PMV20ENR	MOSFET	0.117	5	0.585	D
(multiple)	(various)	~50 passive components	2	1	2	E
10	photodiode	UDT PIN 8844-3	25	1	25	F
14	IR LED	Clairex CE3371	2.77	1	2.77	G
	lens for PD1	6mm dia. double-convex lens	12.38	1	12.38	H
	lens for LED1	6mm dia. plano-convex lens	12.38	1	12.38	H
	PCB assembly	Placing components			14.51	I
	external case		6	1	6	J
	cuvette holder		20	1	20	K
	LCD display		2.4	1	2.4	L
	control panel	External keypad	3	1	3	M
	assembly				10	N
	programming, calibration				120	O
			Total Cost:		**$266.07**	

Notes

A. Representative voltage regulator in similar form factor.

B. Discontinued; price may reflect clearance discounting.

C. Representative tantalum capacitor of same discernable specifications.

D. Representative MOSFET of the same form factor.

E. Lumped sum estimate of various small resistors, capacitors, diodes, and inductors on the board.

F. Based on similar Photodiodes (e.g. First Sensor TO5 series).

G. Based on similar LEDs (e.g. Osram SFH 4851).

H. Based on price quote from Edmund Optics for 1000 (each) plano-convex and double-convex lenses.

I. Based on price quote from Screaming Circuits; assuming 1000 RoHS-certified boards, 25 unique components and 75 placements, with 20-day lead time.

J. Estimate of materials cost ($500) plus cost of injection mold setup ($5500) for 1000 devices.

K. Estimate of cost for machinable plastic ($1000 for 2000 inches of two-inch diameter black Delrin rod, and 3000 inches of half-inch diameter black Delrin rod) and machining labor included.

L. Estimated from existing quotes on Alibaba; possibly cheaper at scale.

M. Based on roughly similar 1x6 membrane keypads available on eBay and Octopart; assuming reduced cost at scale; subsytem assembly labor included.

N. Assuming 15 minutes assembly at $40/hr (wage plus 100% overhead).

O. Assuming 2 hours at $60/hr (wage plus 100% overhead).

The device was easily disassembled by removing four screws and prying the two halves of the casing apart. Components and materials, and their costs, were identified or (where noted) estimated;

labor was estimated. A per-unit price, assuming a production quantity of 1000 units, was calculated at $266.07.

This is intended to be a generous estimate of the true per-unit cost, which could reasonably be lower due to, e.g., purchasing components in larger quantities for cheaper per-unit price, using a longer lead-time for PCB assembly (or doing assembly in-house), or optimizing procedures to reduce the durations of machining, programming, or calibration tasks below their estimates. By the same token, the true per-unit parts-and-labor cost of an HF Scientific may be higher than this estimate due to unforeseen factors.

Appendix E. AWQUA Framework device construction guidelines

User:

Proposed

(U1) A description of the population of end users envisioned (e.g. "rural communities in developing countries").

Prototype – Phase I

(U2) Any new or revised information about the envisioned end-user population description from (U1).

Prototype – Phase II

(U3) A conservative estimate of how frequently calibrations should be performed, based on available information on the measurement mechanism and the testing data for the specific device.

Prototype – Phase III

(U4)* Ease-of-use reports from a tester from a selected and identified range of prototype testers;

(U5) Hardware assembly instructions;

(U6) Device programming instructions;

(U7) Caseware manufacturing and assembly instructions;

(U8)* Operating instructions, including how to take validation, drift, and recalibration measurements;

(U9)* Reports of operational issues from at least two weeks of regular use, in conditions that match the use environment identified in (E5) as closely as is feasible.

Provisional

(U10) Any new or revised information about the envisioned end-user population description from (U2).

(U11) A product introduction video, in English (at minimum), must be produced to familiarize potential customers with the device. This introduction video must be made publicly available online, in a common free video hosting platform such as YouTube (Google 2018).

Registered

(U12) Any new or revised information about the envisioned end-user population description from (U11).

(U13) An updated version of (U11), in English (at minimum), must be produced to familiarize potential customers with the device. This introduction video must be made publicly available online, in a common free video hosting platform such as YouTube (Google 2018).

(U14) Written device operation instructions, in English (at minimum). It is preferred that instructions are also made available in other languages that target previously identified target user groups (if any). These instructions must be made publicly available online.

(U15) Audiovisual device operation instructions, in English (at minimum), in the form of a video user guide. All points in the written instructions, (U14), must be covered in the video user guide. It is preferred that instructions are also made available in other languages that target previously identified target user groups (if any). These instructions must be made publicly available online, in a common free video hosting platform such as YouTube (Google 2018).

Sampling:

Proposed

(S1) A summary of any known sampling issues which may affect the measurement process or the operation of the Proposed device (e.g. “when conducting turbidity measurements cuvettes must be wiped and dried, both to remove any dirt from the outside of the cuvette and to dry the cuvette and prevent damage to the device electronics”).

Prototype – Phase I

(S2) Any new or revised sampling issues encountered since (S1).

Prototype – Phase II

No information required.

Prototype – Phase III

(S3)* If the standards specified in (L3) contain sampling requirements, these must be clearly stated in device documentation and followed whenever a requirement at or beyond this stage requires sampling.

Provisional

(S4) Any new or revised sampling issues encountered since (S2).

Registered

(S5) Any new or revised sampling issues encountered since (S4).

Environment:

Proposed

(E1) A description of the intended geographical areas where device use is envisioned (e.g. “surface water monitoring in tropical areas”).

(E2) Existing literature on the applications of the proposed mechanism for measuring the intended parameter;

(E3) A listing of relevant, currently available commercial monitoring devices;

(E4)* An explanation as to why the proposed device should be developed and employed (e.g., rather than an equivalent existing device being employed).

Prototype – Phase I

(E5) Any new or revised information for (E1) on the intended geographical areas where device use is envisioned.

Prototype – Phase II

(E6) A “Cost at Scale” (CAS) BOM with suggested suppliers and hardware costs for manufacturing runs of 1 to 1,000 units in decades.

Prototype – Phase III

(E7) “Bill of Fabrication” (BOF), which outlines the costs of all equipment and services used to produce the Prototype;

(E8) An estimate of the time, and labor, required to produce a Prototype. (E6) An estimate of the time, and labor, required to produce a Prototype.

Provisional

(E9) Any new or revised information for (E5) on the intended geographical areas where device use is envisioned.

(E10) Setup cost for manufacturing facility, and per-unit cost at scale (1 – 1,000 units in decades), fully detailed.

Registered

(E11) Any new or revised information for (E7) on the intended geographical areas where device use is envisioned.

(E12) Complete costs detailed by independent manufacturer.

Device:

Proposed

(D1) A statement of the intended form factor, power source, use setting, data transmission chain, and actuation mode of the proposed device;

(D2) A detailed sketch of the proposed monitoring device should be documented, which provides visual reference to each of the items identified in (D1).

Prototype – Phase I

(D3)* Circuit description, consisting of a schematic, and either a Printed Circuit Board (PCB) layout (in, e.g., EagleCAD format) or breadboard layout (in, e.g., Fritzing);

(D4)* A Logic of Operations description, detailing how the device will interface with a user, and take, calculate, store, display, and transmit measurements;

(D5)* A diagram of the structural components of the measurement mechanism (e.g. a cuvette chamber or optical window);

(D6) A Bill of Materials (BOM), detailing the electrical components of the measurement mechanism;

(D7)* Datasheets for key electrical and structural components.

Prototype – Phase II

(D8) Circuit design files (e.g. EagleCAD BRD/SCH files, as well as CAM files in Gerber RS274-X format)

(D9) Firmware code in a common language (e.g. Arduino, C, MicroPython, MBED, FreeRTOS);

(D10) Software code, if any;

(D11) A description of the data storage schema used, if any;

(D12) A description and link to any firmware or software libraries used to build the device's code;

(D13) Design files of internal structural elements, if any, in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD);

(D14) Design files of internal structural elements, if any, in a common interchange format (e.g. STL, DXF).

Prototype – Phase III

(D15) Case design files in a common editable format (e.g. F3D, SAT, BLEND, OBJ, SCAD);

(D16) Case design files in a common interchange format (e.g. STL, DXF);

(D17) Durability summary, including a summary of likely failure points of external and internal structural elements;

(D18) A summary of challenges and opportunities in the current Prototype design.

Provisional

(D19) Any design changes made during the Provisional phase, and update the respective documents (schematic & board, BOM & CAS, BOF, caseware files). If changes were made to power train rerun (K7); if changes made to data communication hardware rerun (I4).

Registered

(D20) Any design changes made during the Registered phase, and update the respective documents (schematic & board, BOM & CAS, BOF, caseware files). If changes were made to power train rerun (K7); if changes made to data communication hardware rerun (I4).

Measurement:

Proposed

(M1) A description of the parameter to be measured, and an explanation of the relevance of this parameter to water quality testing;

(M2) A description of the measurement mechanism to be used, as well as other common measurement mechanisms that have been or can be used for the parameter indicated, including a brief comparison of the advantages and disadvantages of the proposed measurement mechanism relative to the other mechanisms listed.

Prototype – Phase I

No information required.

Prototype – Phase II

(M3) A description of the device calibration procedure and re-calibration procedure (if different);

(M4) A description of the procedure by which calibrations will be verified and the measurement precision and accuracy of the device ascertained. This should include consideration for how to measure drift over time and temperature ranges (and appropriate ranges for any other confounder variable identified in [L3] below).

Prototype – Phase III

(M5) If the standards specified in (L3) contain measurement requirements, these must be clearly stated in device documentation and followed whenever a requirement at or beyond this stage requires measurement.

Provisional

See (M2).

Registered

See (M2).

Interactive:

Proposed

(I1)* Descriptions of devices at all stages of the AWQUA development framework must be published in a publicly available online repository (e.g. GitHub).

Prototype – Phase I

No information required.

Prototype – Phase II

(I2) Following completion of all other requirements in Phase II, a static copy of the Prototype Design should be made publicly available through an online repository (such as GitHub) for perusal by interested parties.

Prototype – Phase III

(I3) Following completion of Phase II, a Prototype design must be left unedited for at least two weeks, and promoted to interested parties (e.g. Appropedia, Public Lab, and Akvo). Any comments received during this period must be addressed before proceeding;

(I4) A certification of successful data flow.

Provisional

(I5)* Documented agreement with two suitable external agents to conduct use tests, including device operation, recalibration, and revalidation;

(I6)* Documented agreement with one suitable external agent to construct, calibrate, and validate the prototype device;

(I7)* Ten fully constructed prototype units, at least five of the ten constructed by the external manufacturing agent;

(I8) Following completion of all other Provisional Stage requirements, documentation of the Provisional Design must be finalized and left unedited for at least two weeks. The device and its documentation must be promoted to interested parties (e.g. Appropedia, Public Lab, Akvo). Any comments received during this period must be addressed before proceeding to the Registered phase.

Registered

(I9) Fifty devices constructed by two or more independent manufacturers;

(I10) Testing partnerships established with two or more independent testers;

(I11) All documentation integrated into online repository;

Legal:

Proposed

(L1) Documentation of primary measurement standards and testing procedures (e.g. EPA, ISO, WHO), if any, for the proposed pair of analyte and measurement mechanism;

(L2) A statement acknowledging and crediting all members of the device development team for their contributions.

Prototype – Phase I

No information required.

Prototype – Phase II

(L3)* The specific water quality monitoring standard or guideline for which the Prototype device is intended to be a suitable measurement device.

Prototype – Phase III

No information required.

Provisional

(L4)* All device design files must meet AWQUA documentation guidelines.

(L5)* If the device is open-source, it must have appropriate license(s) (e.g. GNU-GPL [FSF 2007] or MIT [OSI 2006] for software, Creative Commons [CC 2017] for circuit board layout and caseware). Additionally, device documentation must be reviewed for any gaps or errors that would prevent Open Source Hardware Association (OSHWA) self-certification (see http://certificate.oshwa.org/).

Registered

(L6) If open-source, device must meet self-certification criteria as defined by OSHWA, and must be certified and labeled with the OSHWA logo.

Quality assurance / quality control:

Proposed

No information required.

Prototype – Phase I

(Q1) Proof of operational measurement utility must be provided in the form of a basic measurement data set, along with a summary of how the device was operated to obtain the data.

Prototype – Phase II

(Q2) Calibration data, from a calibration procedure conducted according to the water quality monitoring standard selected in (L3).

(Q3) Validation data, from a validation procedure conducted according to the water quality monitoring standard selected in (L3).

(Q4) Drift data, showing the consistency of readings taken with the same Prototype device over time, and across the range of ambient conditions for measurement confounder variables identified in (M4) (or as required by the analyte-specific standard and appropriate for the intended environment of use).

Prototype – Phase III

(Q5) Calibration, validation, and drift datasets;

(Q6) Recalibration data, showing the agreement of a calibrated device before and after recalibration;

(Q7) A power drain analysis and estimate of use per charge cycle or battery change (if applicable).

Provisional

(Q8)* Operation, recalibration, and revalidation data from independent testers;

(Q9)* Construction, calibration, and validation data from independent manufacturer;

(Q10)* Long-term use – bug reports and usage reports from at least two weeks of daily use of ten prototype units, which must take place in the intended environment of use identified in (E5);

(Q11) Standard-specific review of data (showing how the data collected meet the requirements of the stated primary or secondary monitoring standard).

Registered

(Q12) Operation, recalibration, and revalidation data from independent testers;

(Q13) Construction, calibration, and validation data from independent manufacturer;

(Q14) Long-term use – usage reports from at least six weeks of daily use of 25 prototype units;

(Q15) Bug reporting integrated into online repository for design.

Curriculum Vitae

Christopher Kelley

Born: Houston, Texas on November 29, 1979.

EDUCATION AND TRAINING

2018 PhD, Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD. Dissertation: “A proposed framework for the development and regulation low-cost water quality monitoring devices”. Adviser: Dr. William Ball

2010 BS, Civil Engineering (Environmental Engineering Focus), University of Texas at Austin, Austin, TX

2002 BA, Philosophy (Plan II), University of Texas at Austin, Austin, TX

RESEARCH AND PROFESSIONAL EXPERIENCE

Oct 2016 - Oct 2017 Johns Hopkins University

Lead Hardware Designer on Smart Cities Air Challenge Grant

Responsible for the electronics and firmware design, fabrication, assembly, testing, and calibration of 300 low-cost, open-source air quality monitoring stations for the City of Baltimore.

2014-2017 Johns Hopkins University

Graduate Student Lead, Graduate Student Lead for EPA P3 grant award (Phase I & II)

Researched, designed, prototyped, and tested novel low-cost, open-source water quality monitoring devices. Perform field tests in tandem with community partners in Kenya and Honduras. Implemented and run an SMS-to-server communications network for drinking water treatment plants, that monitors the daily water quality for over 30,000 people in eight communities in Honduras.

2011-2013 Johns Hopkins Center for Communications Programs

Software Design Intern

Design and augment decision support systems for local and international development agencies. Tasks included customized installations of Ushahidi, FrontlineSMS, and ArcServer. Work often involved writing software to facilitate data sharing between existing software solutions.

2011 TetraTech ARD

Statistical Consultant

Conducted statistical analysis of household survey data on sanitation practices in several provinces in Afghanistan for USAID-funded project. Final report also evaluated data gathering and processing, database security, and survey methods.

2009-2010 The University of Texas at Arlington Center for Environmental Excellence

Software Developer

Designed turnkey solutions for processing drinking water sample data for the State of Texas, from reporting by water testing laboratories to receipt and validation of data, and preparation for compliance processing. Provided technical assistance to laboratories and state regulator, including on-site needs assessments.

2006-2009 Texas Commission on Environmental Quality

Natural Resources Specialist (2006-2008); Engineering Intern (2009).

Managed inventory and sampling data for all drinking water in Texas, conducted federal reporting to the EPA, built data management applications to ensure data integrity and ease of use. Also, evaluated data flow to detect lapses in regulatory efforts and robustness of business processes. Evaluated proposed changes to the design of public drinking water systems.

COMPUTERS

Operating Systems – Linux, Windows, Mac.

GIS – ArcMap, QGIS, OGR/GDAL, PostGIS, GeoR, Leaflet, GeoExt, KML, SLD.

Databases – MySQL, PostgreSQL, MS Access.

Web Programming – HTML, CSS, Javascript, PHP, Node, AWS, D3, PaperScript.

Other Programming – C/C++, C#, Unity3D, Python, R, VB/VBA.

ELECTRONICS HARDWARE DESIGN

Schematic Design and Layout – EagleCAD, KiCAD, Upverter.

Assembly and testing – Through-hole and SMD placement, reflow soldering, hot air rework, oscilloscope, logic analysis, stencil fabrication.

Microprocessor programming – Atmel Studio, Arduino, avr-gcc, MBED.

Microprocessor platforms – AVR, ESP8266, ESP32, STM32, Nucleo, Teensy.

OBJECT DESIGN

CNC: Tormach, ShopBot, XCarve, Carvey

3D printing: Makerbot, Formlabs SLA, RepRap

Laser cutting: Epilog, Boss

Software: Fusion360, VCarve, OpenSCAD, Inkscape

PROFESSIONAL ACTIVITIES

Member, Sanitation Advisory Committee to the Mayor of Baltimore

LANGUAGES

English—Fluency (written and oral)

Mandarin Chinese—Advanced (written and oral)

Spanish—Intermediate (written and oral)

AWARDS AND FELLOWSHIPS

EPA Smart Cities Air Challenge Grant (2017). $40,000

Infy Maker National Award (2016). $10,000

EPA People, Prosperity, and Planet (P3) Award (2014-2017). $105,000

Abell Award for Urban Policy in Baltimore (2016). $5,000

IGERT Fellowship: Water, Climate, Health Fellowship for Graduate Training (2014-2016), $50,000

Environment, Energy, Sustainability and Health Initiative Fellowship (2013-2014). $30,000

PUBLICATIONS (379 citations)

Kelley, C. D., Krolick, A., Brunner, L., Burklund, A., Kahn, D., Ball, W. P., & Weber-Shirk, M. (2014). An affordable open-source turbidimeter. Sensors, 14(4), 7142-7155.

Kelley, C., Lee, P. F., Ding, T. S. & Sarkar, S. 2009. Biodiversity Conservation in an Urbanized Insular Landscape: Identifying Priority Areas for Bird Species in Taiwan. Pacific Conservation Biology.

Levin, D. A., Kelley, C. & Sarkar, S. 2009. Enhancement of Allee effects in plants due to self-incompatibility alleles. Journal of Ecology, 97(3), 518-527.

Sarkar, S., Crews-Meyer, K., Young, K., Kelley, C. & Moffet, A. 2009. A dynamic graph automata approach to modeling landscape change in the Andes and Amazon. Environment and Planning B, 36, 300-318.

Sarkar, S., Fuller, T., Aggarwal, A., Moffett, A., & Kelley, C. 2009. The ConsNet Software Platform for Systematic Conservation Planning. In: Spatial Conservation Prioritization:

Quantitative Methods and Computational Tools, Moilanen, A., Wilson, K. A., Possingham, H. (eds). Oxford University Press

Pawar, S., Koo, M. S., Kelley, C., Ahmed, M. F., Chaudhuri, S. & Sarkar, S. 2007. Conservation assessment and prioritization of areas in Northeast India: Priorities for amphibians and reptiles. Biological Conservation 136(3), 346-361.

Sarkar, S., Justus, J., Fuller, T., Kelley, C., Garson, J. & Mayfield, M. 2005. Effectiveness of Environmental Surrogates for the Selection of Conservation Area Networks. Conservation Biology 19(3), 815-825.

Kelley, C., Garson, J., Aggarwal, A. & Sarkar, S. 2002. Place prioritization for biodiversity reserve network design: a comparison of the Sites and ResNet software packages for coverage and efficiency. Diversity and Distributions 8(5), 297–306.