FEASIBLE – REAL-TIME ACOUSTIC ANALYSIS OF BATTERIES

APPLICANTS & AFFILIATIONS

Dr. Andrew Hsieh, Dr. Barry Van Tassell, Dr. Shaurjo Biswas, Princeton University Department of Mechanical and Aerospace Engineering, Princeton University's Andlinger Center for Energy and the Environment, Cyclotron Road, Feasible, LLC; Prof. Daniel Steingart at Princeton University MAE/ACEE

INTELLECTUAL PROPERTY STATUS, PATENT OR TECH TRANSFER NUMBER(S)

We have filed a full patent application (US Patent Application 14/610,219), which Princeton will own; we are currently negotiating terms for exclusive commercial license to our company, Feasible. The patent describes the ultrasonic testing apparatus, control software, its broad applicability to a wide variety of battery-related uses, and data management and analysis methods to determine battery state.

TIME TO MARKET - Within the next 12 months

C2M OBJECTIVES

Our acoustic battery diagnostics technology has a range of possible applications within the battery industry: R&D, quality assurance/control in manufacturing, battery management systems, and the second-life (repurposed EV battery) market to name a few.

A lot of these markets are either emerging or relatively non-transparent, so by participating in the C2M program we hope to be able to get a more quantitative measure of how much a better battery diagnostic technology is worth. For example: How much is it worth to decrease iteration times in R&D? How much are companies willing to pay if we could extend the operational lifetime of their batteries by 20-30%? How much is it worth to a manufacturer or a battery user to prevent a defective cell from entering their devices?

Then, based on that sort of market analysis, we hope to answer questions such as: Which markets are the best opportunities for us to target? What will be the most effective business model for bringing our technology to market? What kinds of costs can those markets carry?

TECHNOLOGY

We invented a method for determining the state of charge, state of health, and physical structure of any closed battery using acoustic interrogation. This low-cost, non-destructive, and scalable technology could reduce the time and cost of battery development, manufacturing, and qualification by
validate performance quality. Inline testing of state of charge and state of made, tested, and managed everywhere.

Our acoustic battery analysis technology is poised to address several of the critical needs in the battery industry. The incumbent approaches towards battery diagnostics are either slow, expensive, invasive, inaccurate, or a combination of those. In contrast, ultrasonic analysis is inherently fast, non-invasive, sensitive, and inherently scalable and easily automated.

We have demonstrated our method on over 30 different battery types (i.e., combinations of battery chemistry and form factor) and have observed clear acoustic signatures that correlate strongly with how much charge is left in a battery, its remaining lifetime, and its internal structure. We have developed an evolving prototype toolkit for battery researchers, and have carried out on-site demos or in-house testing for several battery companies.

CUSTOMERS

One of the major pain points in the battery industry is the fact that there is no fast, accurate, cost-effective way to see the physical processes that take place within a battery during operation. Some of these processes are the basis for how a battery works, but others are responsible for why batteries eventually fail. By providing direct physical insights during operation, we can improve how batteries are made and developed, we can optimize performance to increase total energy output and lifetime, and give enough lead time to prevent catastrophic failures from ever occurring.

Also, in the emerging market for repurposing retired EV batteries, one of the major pain points is the speed with which packs and modules can be tested for quality. A single acoustic reading takes < 1 s (vs. 15 minutes up to several hours for electrical techniques), so throughput can be dramatically improved with acoustic analysis.

SCALING

Our current hardware has a ~$10k bill of materials for a 6-channel unit (a software and analysis tool would also be included as part of the product). We think this is suitable for some markets (R&D, high-value systems), however we are aiming to get to below a $1k hardware cost for manufacturing and large-scale applications. We envision an every-sensor-per-cell environment, however we will need to get to our hardware costs to below $1/sensor in order for that to be realized.

ADVANTAGES

Direct detection of physical changes in commercially relevant batteries requires x-ray and electron methods or synchrotron light sources. These are effective, but expensive and not scalable or deployable in commercial installations. In manufacturing, high-throughput screening typically involves inexact electrical and strain-based testing, and expensive x-ray imaging. After assembly, days to weeks
validate performance quality. Inline testing of state of charge and state of cycling are needed per batch to detect flaws and health is done mainly with electrical techniques, which are impractical as they interrupt operation, deplete charge, and only provide cell-averaged information and abstractions of internal features; in the worst case, the battery is destroyed.

A benefit to our technology is that the behavior of sound in a cell is sensitive to any changes in physical properties along the path of the acoustic waves. As a result, ultrasonic analysis gives direct, detailed information about internal battery components, which electrical and strain-based methods cannot. Another advantage is that each reading takes < 1 s, enabling a high time resolution, which is valuable for detection of high-rate phenomena. Fast readings also open up possibilities in manufacturing environments, and the hardware is cost-effective and scalable. Correlations of acoustic behavior to manufacturing and performance quality could lead to cost savings and faster validation times."

**BARRIERS**

In the best-case scenario, the hardware can be reduced to a MEMS-level, every-system architecture. The extent that cost can be driven down depends on the economies of scale and on the signal quality that can be directly used in online BMS packages. Preliminary conversations with domain experts indicate that this is possible. Additionally, we have observed high-quality signals and correlations for many different battery chemistries and geometries using commercial off-the-shelf ultrasonic systems. What remains to be seen is if measurement repeatability and quality is maintained as we decrease the cost and geometric footprint of the ultrasonic hardware. We are optimistic this can be extended to online/inline BMSs in a cost effective manner. Even in the worst case, with custom transducers and holders to standardize alignment and contact pressure, this technology can scale to R&D labs and QA/QC applications.

**FEEDBACK**

We’re currently in the UC Berkeley’s Startup Accelerator program and have been doing extensive customer discovery as a part of it. Though we are early in the development of the technology, there has been a tremendously positive response to our technique from across the battery industry.

Everyone who is knowledgeable of the battery industry is excited by the prospects for our technology. Additionally, we were recently accepted into the second cohort at Cyclotron Road, and have received strong interest from a few venture firms in providing seed.

**ACADEMIC/JOB TITLE(S)**

All Princeton Postdoctoral Researchers, transitioning to Cyclotron Road, Cohort 2
STATUS

Company or LLC formed, ARPA-E project, Cyclotron Road participant, Bench scale prototype(s); Significant lab performance data, Founder(s) only

TIME TO MARKET BACKGROUND

The battery R&D market is a very low-hanging fruit: numerous battery R&D companies and academic labs have asked (some repeatedly so) when we will have our first product out. We placed our time to market as “within the next 12 months” with that market in mind, as the non-recurring engineering needed to get to the right cost point is minimal. Our plan is that in year 2-3, we will start to make headway into the battery manufacturing market (one company has asked us when we will have a product for in-line quality control for cell assembly, and we are talking with a couple of other larger battery producers as well regarding QC/QA). Battery management and second life markets are further out (3-5 years), not only because the technological challenges are much greater, but also because the players in those markets are much more cautious, given the technical risks.
Summary - Ultrasonic Battery Analysis

We invented a method that uses ultrasound to measure the state of charge, state of health, and structure of batteries. This is a new technology that will enable battery developers to iterate faster, manufacturers to assemble and validate cells more efficiently, and device makers to use batteries more effectively. It will change how batteries are made, tested, and managed.

The development of next-generation batteries is arguably more important now than it has ever been, because the pace of battery development is slower than the technologies that depend on them: things like affordable long-range EVs and a grid that runs on renewable energy all require higher-performing batteries, which we do not have yet. Our vision is to use ultrasound for batteries to address some of the main pain points in the battery industry.

A major bottleneck is the difficulty of directly measuring the physical changes inside a battery during operation. Battery manufacturers can control what goes in a cell and monitor and optimized how it is assembled; however consistency is still an issue. Also, once the can is closed or the pouch is sealed, the level of control and clarity is reduced to nearly zero. This is a problem because the materials in a battery change during use, and how it is used (and how well it was made) affects long-term performance. As such, the ability to see inside batteries during operation is critical for new battery development: to improve how we make batteries, to inform the way we use them to maximize performance, and to figuring out how and why they fail.

There is currently no accurate, scalable way to see inside conventional batteries during use: X-ray or photon sources are accurate, but are expensive, and are not suitable in commercial installations. Electrical techniques are cheap but impractical, as they interrupt operation and provide inaccurate information on cell state. Furthermore, AC impedance, which is the standard for battery health testing, can take several minutes per scan. The need for cost-effective, fast, accurate real-time analysis of batteries is a major pain point, and our technology meets that demand.

Electrochemical-acoustic (EA) analysis is achieved by applying an ultrasonic pulse to the battery and listening to the echoing behavior. An advantage of this technique is its sensitivity to changes in physical properties along the acoustic path. Also, as each reading takes < 1 ms, accurate real-time detection of physical dynamics is possible, and this technique can probe both lab and commercial scale cells. We have tested this extensively: on smartphone cells, on the cells found in Tesla’s Model S, and on new batteries being developed for the grid. Without exception, every single cell has shown clear, unique acoustic fingerprints during cycling. With a database of fingerprints, a cell’s charge, remaining lifetime, and structure can be determined from just a few waveforms.

Our technology is completely new to the field. It is cheap, scalable, and non-destructive, and can easily be incorporated into tools for R&D and manufacturing, and into sensors and algorithms for battery management systems (BMSs). By providing real-time, accurate data about the physical changes occurring in a battery, EA analysis will improve the speed of battery development and manufacturing, and will also help batteries be utilized and re-purposed more effectively. Ultrasound for batteries will enable the efficient generation, storage, and use of energy worldwide.

Our Vision

We have shown that the behavior of sound in a battery is fundamentally related to its performance. Our vision is to develop a technology that all battery manufacturers and users will employ to better understand and utilize their cells. We will transform our peer-reviewed, patent-pending acoustic method into fast, low-cost, non-invasive, and accurate tools for determining battery state of charge (SOC), state of health...
(SOH), and physical properties and defects. We are among the first to use acoustics to test batteries, and believe we are the first to demonstrate the fundamental link between electrochemical-physical state and acoustic response. Acoustic analysis is a technology that battery developers can use for diagnostics, battery manufacturers can use for quality control (QC) and to speed up validation, and battery users can employ in BMSs to improve cell lifetime and improve safety; it can also support the emerging market for second-life (recycled EV) batteries. This tool will reduce the time and cost of battery development, manufacturing, and qualification by directly linking performance and structure. If wildly successful, this will change how batteries are made, tested, and managed everywhere.

Despite the impressive capabilities of currently-available chemistries, and despite significant investment in research efforts, the development of new battery technologies remains slow, and manufacturing and implementation remain expensive. In broad strokes, this is because:

1. Battery manufacturing is still too much of an “art”: cell performance is sensitive to changes in layer thickness, spacing, and alignment during assembly, and often days to months of cycling are required per cell before flaws are detected.
2. There is no commercially-viable method to physically and directly “see” inside batteries during cycling, making it difficult to ascertain SOC and SOH, not to mention actively manage cycling to optimize performance and lifetime, and to improve safety.

Our plan is to: i) develop software and PCB-level hardware for acoustic battery analysis; ii) establish footholds in the benchtop, QC/validation, and second-life markets; iii) design prototypes of MEMS-level devices. We will then be in a strong position to raise the capital necessary to produce the MEMS hardware and enter the BMS market, while maintaining strength in the R&D and manufacturing markets.

**Overview of Incumbent Technologies**

Direct detection of physical changes in commercially-relevant batteries requires x-ray and electron methods or specialized equipment such as synchrotron light sources. These are effective, but expensive and not scalable or deployable in commercial installations. In manufacturing, high-throughput screening typically involves electrical and strain-based testing (which is inexact) and x-ray imaging (which is expensive). After assembly, days to months of cycling are needed per batch to detect flaws and validate performance quality. Inline testing of SOC and SOH is done mainly with electrical techniques, which are impractical as they interrupt operation, deplete charge, and only provide cell-averaged information and abstractions of internal features; in the worst case, the battery is destroyed and cannot be reused.

**Our Approach and Advantage**

In ultrasonic nondestructive testing, the propagation of ultrasonic waves in an object is measured; while commonly used in construction and metal manufacturing, it has never before been applied to batteries. Our method repurposes the testing equipment (ultrasonic pulser/receiver and transducers) to actively probe changes in the acoustic behavior of cells during cycling. This is possible because the behavior of sound traveling through a battery is sensitive to the physical properties of its internal components (particularly layer thickness, density, and modulus), and especially to how they change during cycling. This is measured by applying a well-defined acoustic pulse to the battery, enabling both sudden events (e.g., cracking, delamination) and gradual phenomena (e.g., changes in SOC/SOH, formation of passivation layers) to be observed. Single waveform (snapshots in time) and acoustic difference (time-resolved “fingerprints”) data are obtained, and as readings do not deplete any charge, this approach can provide in operando determination of the physical state of batteries. Of particular importance is the ability to effectively probe both lab scale and commercial scale cells.

A benefit to this technique is that the behavior of acoustic echoes in a cell is sensitive to any changes in physical properties along the path of the acoustic waves. As a result, ultrasonic analysis gives direct,
detailed information about internal battery components, of which electrical and strain-based methods are unable to provide. With multiple sets of transducers, spatially-resolved analyses can also be carried out. Another advantage is that each reading takes < 1 s, enabling a high time resolution, which is valuable for the detection of high-rate phenomena, such as internal shorts or thermal runaway. Fast readings also open up possibilities in manufacturing environments. The hardware is cost-effective and scalable, and transducers can be designed into rollers and other components. Correlations of acoustic behavior to manufacturing and performance quality could lead to cost savings and faster validation times.

This non-electrical, non-destructive technology will be adapted to meet the needs of battery R&D labs, manufacturers, and users in a cost-effective manner. Ultrasonic analysis will allow battery development to iterate faster, cells to be assembled more efficiently, and batteries to be used more effectively. Furthermore, the ability of this method to determine SOH non-invasively may support the emerging market for second-life cells, which would help offset the high cost of electrochemical energy storage and facilitate a more sustainable energy future.

**Technical Risks**
In the best-case scenario, the hardware can be reduced to a MEMS-level, every-system architecture. The extent that cost can be driven down depends on the economies of scale and on the signal quality that can be directly used in online BMS packages. Preliminary conversations with domain experts indicate that this is possible. Additionally, we have observed high-quality signals and correlations for many different battery chemistries and geometries using commercial ultrasonic systems. What remains to be seen is if measurement repeatability and quality is maintained as we decrease the cost and geometric footprint of the ultrasonic hardware. If these can be driven down far enough, it could catalyze a paradigm shift to a “batteries as a service” environment. We are optimistic this can be extended to online/inline BMSs in a cost effective manner. Even in the worst case, with custom transducers and holders to standardize alignment and contact pressure, this technology can scale to R&D labs and QA/QC applications.

**Market Opportunity/Commercialization Plan**
Our ultrasonic analysis technology offers battery researchers, battery manufacturers, and device makers a cost effective, non-electrical method for determining the SOC, SOH, and physical condition of cells.

An ultrasonic diagnostic tool for battery R&D labs (Phase 1) is a low-hanging fruit, with an estimated $5-10M market that we can address with the current hardware. The value proposition is better physical insights and faster iteration times. Initial conversations with potential customers have been very positive. A key feature of our method is < 1 s readings, which opens up possibilities in high throughput QA/QC and performance validation tools for battery manufacturers (such as Tesla’s Gigafactory). The value proposition here is higher yields and better operational margins. The market for QA/QC and validation (Phase 2) is ~$20-60M, and with development efforts at the PCB level, could be addressed within 2 years.

In the longer term, as we develop reliable control algorithms and further reduce hardware costs, ultrasonic sensors can be incorporated into BMSs for stationary storage and large-device applications (Phase 3, $100-500M est. market), which we plan to address within 3 years. Ultimately, within 5 years, the hardware can be reduced to MEMS level and become an every-cell, every-system architecture. If realized, ultrasound sensors could be deployed in BMSs in any device with a battery (Phase 4, $1-3B est. market) and used for predictive maintenance of storage systems to minimize downtime. There are multiple value propositions here, which mostly revolve around increased utilization and operational efficiency. Our technology may also support the emerging market for second-life (recycled) cells and help offset the cost of electrochemical energy storage. The value proposition here is higher testing throughput, leading to more packs being repurposed, lowering the cost of EVs to the consumer. According to Navigant Research, this $16M market is projected to grow to $3B by 2035; we aim to enter it within 2 years.