Graduate Research Plan Statement **Alex Yen**

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Introduction and Background: Global access to reliable power is a problem. Taneja et al. found that while the electricity infrastructure is rapidly expanding in developing countries, the usage of electricity by homeowners and small businesses is not; increased physical access to electricity does not imply *dependable* access [1]. Fine-grained, last-mile measurement is expensive and slow to deploy – e.g. smart meter penetration has only reached 57% in the United States as of December 2020 [2]. In practice, up to 80% of outages occur on this unmonitored, low-voltage infrastructure, which leads to end user reliability far detached from reported metrics [3]. In developing countries, this end-user unreliability stymies electricity adoption and limits economic development [4]. The natural question, then, is what infrastructure is needed to improve grid reliability?

Information on grid infrastructure is also often undocumented or outdated. For instance, the University of California San Diego (UCSD) possesses only a paper map of streetlights located on campus; this physical map dates back to pre-2002 and has not been updated since. This is due to the exhausting effort it would take to *manually* update the mapping amidst rapidly changing campus infrastructure. New buildings will be built, and old infrastructure will be torn down by the time the infrastructure is remapped, resulting in (yet) another outdated map. Inaccurate maps—or no maps at all—result in inefficient responses to power issues and power failures [5].

My current research aims to autonomously generate high resolution grid mapping information with commodity cameras. **I hypothesize that we can use cameras to perform autonomous mapping and real-time monitoring of the electric grid**. The foundation of this approach will map the low-voltage power grid via imaged streetlights and building lights (i.e. night lights). In laboratory conditions, our initial work has shown that smartphone cameras can extract key properties—such as frequency and phase—simply by observing light bulbs. I will research on the deployment of vision-based devices that can extract the phase and voltage of all night lights within a city. This proposed research takes the first principles developed in controlled, stationary, and laboratory settings and solves the systems problem required to enable real-world, wide-area deployment.

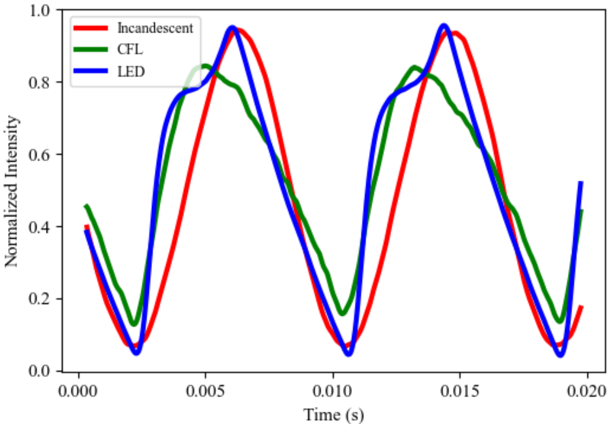

Figure 1. Example BRF waveforms.

Previous Work: Light bulbs receive an Alternating Current (AC) waveform as input; imperceptible to the human eye, this AC input changes the intensity of light output by light bulbs. We call this light output a Bulb Response Function (BRF) [6, 7], which we use to estimate properties of light bulbs; we then reversed this function to estimate grid metrics. I extracted BRFs by sampling the intensity of a lightbulb with a phototransistor-based chip and an oscilloscope; example BRFs are shown in Figure 1. These same BRFs were also extracted through a camera's rolling shutter effect [6, 8]. These resulting BRFs allowed us to indirectly measure phase and frequency of the electric grid through lightbulbs. We also extracted the voltage of a light through the inverse square law – this depends on the lightbulb's intensity of illumination as well as the distance between the camera's 3-dimensional (3D) location—i.e. Global Positioning System (GPS) location—and a light's 3D location.

Research Plan: To test my hypothesis, I divide my proposal into three stages.

Stage 1: Phase Mapping. In general, a basic mapping requires two sources of information: a location and metadata at that location. For a grid mapping, this is (1) GPS location and (2) phase. I will place vision-based devices on moving vehicles with frequent stops (e.g. public buses) to image the majority of lights amidst a city; this is extended beyond stops in **Stage 3** with motion. Once I extract the phases of lights and their global locations, I will interpolate and trace the lights that are on the same phase – this will form the actual mapping. The challenge with this stage's evaluation is that ground truth mappings and ground truth GPS locations are difficult to acquire; we can address this through small-scale yet extensive, manual measurements and validation.

Stage 2: Autonomous Location Inferencing and Voltage Monitoring. To enable accurate voltage monitoring requires precise distance estimation. In our proof-of-concept, voltage estimation relied on *known* distances between the camera and an observed light [6]; stereo imaging now allows us to calculate this distance. However, computing voltage accurately with images would require GPS estimations of phone and streetlight locations to be centimeter-level accurate; I can currently calculate the distance between these GPS locations with error as little as 3 meters. My research will use multiple images with external methods, such as multi-view geometry, to improve position estimation of a particular night light; accurate distance estimation will enable accurate voltage estimation. I will then quantify the minute changes in pixel intensity that reflect minute voltage fluctuations. Combining pixel quantization with distance estimation will allow me to calculate the voltage of distant night lights in the world.

Stage 3: Deployment at Scale and Handling Motion. Our vision-based devices will be deployed on moving vehicles (e.g. busses); devices will image streetlights as they are transported around a city. However, deployment on moving vehicles will be particularly challenging as motion will induce new complications (i.e. blurring) to the system. To account for this issue, I will explore the tradeoff between high shutter speeds and light sensitivity (i.e. ISO). I will also consider the use of high framerate video – this will not only minimize blurring but also allow for the use of Structure from Motion, an imaging technique that can recover 3D information from 2-dimensional image sequences. Deployment will be targeted in Accra, Ghana; affiliated researchers—whom I can establish a partnership with—deployed state-of-the-art sensors to monitor electricity reliability that will allow me to cross-validate my results [3].

Intellectual Merit: Electricity is indirectly measurable through a wide variety of applications, including (but not limited to) fans [9] and now visible lights [6, 10]. My proposed research explores the use of computer vision to sense and monitor electricity via night lights. The use of cameras to extract phase and voltage information of the power grid enables new ways to autonomously measure and map our existing infrastructures. Furthermore, my research proposes a novel method of measuring voltage – computer vision enables voltage measurements of many lights that are captured in images.

Broader Impacts: Vision-based sensing enables ubiquitous grid-monitoring. My work will improve electricity reliability for customers by providing technology to autonomously map and keep grid documentation up to date. More access to dependable electricity will result in increased electrification, a key indicator of development. Voltage monitoring is also particularly important in developing countries – the large fluctuations in voltages—above and below the nominal value—can be harmful to every-day devices. Grid mapping and voltage monitoring will provide the means to uphold reliability standards, and our cost-effective technology will enable progress towards global access to reliable power.

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