Mobile High Voltage Power Line Thermometer

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Abstract. Modern power grids perform systematically important tasks with immense capital investment behind them. Infrastructure monitoring is an important field in this industry to guarantee safety, prevent damages and optimize transmission. Accurate readings of environmental variables also help power operators design new infrastructure. Operators address this by visual monitoring, and through the use of sensors placed on high voltage lines. Traditionally, these sensors are permanently installed and require lines to be powered down for deployment and removal. The required disruption of service is associated with high costs and therefore undesirable. Axiomatic Design Theory highlighted unnecessary coupling between disruption and measurement as an opportunity. This paper details a design for a thermometer unit that can be deployed to and removed from a live power line. The device can provide temperature measurements to be used in conjunction with visual LiDAR scans to model the behavior of high voltage lines at different load levels to gauge line sag. Mechanisms were designed to safely fasten the thermometer to a live high voltage line via a VTOL drone and for it to detach given a preset time. In case of system failure, the device removes itself through a variety of redundant failsafe mechanisms inspired by the Information Axiom. The success of key design concepts was confirmed through 3D printed prototype testing on a section of a surrogate conductor line in a controlled environment.

1. Introduction

The power grids of most modern countries perform systematically important tasks with an immense amount of capital investment behind them. According to the International Energy Agency, there was a yearly global investment in the range of 273–306 billion USD into electricity networks between 2015 and 2019 [1]. As such, power infrastructure monitoring is an important field in this industry to guarantee safety, prevent costly damage and optimize power transmission. It is important to monitor the health of power equipment to prevent costly damage and optimize maintenance. In addition, getting accurate readings about environmental variables helps power grid operators analyze and manage their grids and design new lines based on evaluations of the usage and utilization of existing power lines.

Modern power transmission grids are the backbone of industry and production. With increased power demand the commission of new power lines is required. These new lines are designed based on data available about lines already in operation. A variety of data are collected during monitoring and surveillance of active power lines.

Power grid monitoring and automation begin forming as a field in the 1920s. The main goal was to connect the operations of power plants and nearby generating stations for operational cost benefits [2]: load and frequency had to be monitored to accomplish this goal.
Requirements have grown since the 1920s, and an important aspect of modern grid maintenance is temperature and sag monitoring. Operators of power grids monitor the wire temperature as increased wire temperatures also mean increased line sag. The now lower hanging power lines can also be an electrocution hazard to individuals [3]. For this reason, most modern countries have legal frameworks in place that define minimum ground clearances for power lines [4]. These regulations aim to make sure that power lines maintain necessary clearances from environmental objects. Line sag is strongly correlated with changes in the wire temperature. The temperature is influenced by outside temperature, load, weather especially precipitation, and the wire’s properties. Transmission system operators can use temperature measurements in conjunction with LiDAR scans of the power line to develop an analytical model with the conductor temperature as the input and the line sag as the output. The model is then used during the design and dimension of new power lines.

The current state of the art focuses on monitoring stations performing long-term measurement and securely attaching to the power line; more details will be discussed in Section 2. This concept requires durable devices hardened to survive extreme weather conditions for long periods. In addition, the line must be turned off for the maintenance personnel to attach the device, remove the device, or service it. Due to the long operation period and lost revenue associated with such actions, line operators must budget carefully in terms of time and money. The long operation time also increases the cost and power-budget requirements of such devices. The authors wondered if there might be a way to choose a different paradigm for line monitoring that might make these challenges easier to address. As will be explained shortly, Axiomatic Design provided the key to designing a new concept better able to meet the needs of this industry.

1.1. Methodology

The general process used to design the sensor mainly follows the Generic Product Design Process outlined by Ulrich et al. [5]. However, it also integrates with Axiomatic Design and Collective System Design theory to formally define design elements and Functional Requirements (FRs), and analyze them concerning coupling.

Axiomatic Design (AD) is a methodology created by Nam Pyo Suh [6] to provide a generic method to design mechanisms with a focus on the manufacturing industry. Axiomatic Design uses Design Parameters (DPs) to facilitate the design of modular and robust systems through the application of two axioms. The Independence Axiom states that the designer must eliminate undesired coupling to keep FRs independent. The Information Axiom mandates that the design should minimize information content i.e. minimize the probability that the FRs are not met. This method utilizes a design matrix to detect coupling between FRs and DPs.

Collective System Design (CSD) was developed by David S. Cochran [7] to make Axiomatic Design more approachable to the automobile manufacturing industry.

CSD instead partitions DPs into Physical Solutions (PSs) and quantifiable metrics. The design matrix is replaced with a box and arrow diagram called a Collective System Design Decomposition (CSDD) to detect coupling in the system. Arrows indicate coupling and should never cross; non-vertical arrows indicate undesirable coupling that needs to be eliminated when possible (Independence Axiom). CSD is Cochran’s answer to simplify some aspects of Axiomatic design that many find complicated to apply.

After the problem was identified, the design team moved on to identifying CNs to the product and mapping these to FRs. From there, metrics were defined that the product would have to fulfill. The metrics were used to drive concept generation and selection. This part of the process was somewhat iterative as interviews were conducted at different stages of the process and the information gleaned in them had to be used to the fullest.
1.2. Customer Needs
As with any design process, we need to gain insight into the stakeholders to ensure the solution makes sense. The target users of our product are Icelandic Transmission System Operators (TOS) and Service Providers. Based upon the feedback from these stakeholders i.e. “customers”, the product is likely to be appropriate worldwide.

The Generic Product Design Process[5] method was used to develop the customer needs (CNs) for such a product. In general terms, this method revolves around identifying explicit, unfulfilled, and latent CNs through interviews and customer interaction. Results are analyzed critically to prioritize, consolidate, and build a hierarchy. The following explicit and/or unfulfilled CNs were compiled from discussions with the local service providers and operators, Svarmi [8] and Landsnet [9]. The top-level need identified was “CN0 Measure the surface temperature of high voltage conductor lines” which can be decomposed into:

CN₁ Accurate data about conductor temperature.
CN₂ Gather data over up to two weeks.
CN₃ Deploy it quickly and without too much hassle.
CN₄ Have no worries about the equipment
CN₅ Remove any equipment from a line reliably and easily
CN₆ Analyze the data reliably
CN₇ Have no worries about my safety or damage to my surroundings.

From the development of these needs, it is clear that the customer is interested in increasing convenience. We continue with a survey of existing products for power line sag evaluation. This survey gives the context of what the customer’s current offerings are.

2. Prior Art
Currently, there are several standardized methods to monitor the sag of power lines:

• Sending out in-person teams that pass along the power lines to monitor the sag.
• Drone surveillance with a camera, LiDAR and/or temperature sensors[10]
• SAR (Synthetic-aperture radar) satellite data[11]
• Sensors on the line that measure position and/or temperature

Customers considered sending out teams to be outdated due to inefficiency and high personal cost. Drones surveillance is an exciting prospect, but are not able to measure for sustained periods in a single location; they are more appropriate to check problem areas on a routine basis. Direct drone measurement also requires an operator for the drone during the measurement. Radar measurement is an exciting new technology, but it is not universally available. The customers contacted currently consider sensors on the line to be the best mechanism to gather the needed data so the authors focused on investigating existing products in that category.

The ASTROSE® sensor (Figure 1a) is a power line sensor developed by the German Fraunhofer Institute for Reliability and Microintegration IZM [15][16]. It can measure the inclination, torsion, and current of the power line it is permanently attached to. Sensors are up to 500 m apart and the signal is sent through the chain of sensors to a base station. The sensors harvest the power from the power lines and do not need any battery.

LAKI is an Icelandic startup that focuses on power line monitoring and surveillance [17]. Their main product is a sensor station (Figure 1b) that is attached to a power line. The station can be equipped with various sensors like cameras, thermal sensors, etc. They claim their station can harvest significantly more power from the attached line than their competitors. The camera feed can be used to detect sag or ice on the line.
Kadtronex is a British company that builds basic temperature sensors (Figure 1c) that can be attached to a power line [18]. The sensors themselves are connected to a node at the base of the pole and communicate with other nodes or a cloud-based server. The data can then be monitored in real-time.

All the investigated products can measure and monitor the surface temperature of power lines. Their general concept is very similar: you attach a sensor permanently to a power line and monitor the temperature. You can either read out the data in real-time or read out their logs afterward. None can address CN_3 and CN_5 regarding easy deployment and retrieval. The authors were not able to find an existing commercial solution that can meet those requirements in particular. This indicates that there is an opportunity to innovate with a new design that can meet all of these needs.

2.1. Functional Requirements
With the background of the product and the CNs now defined, it was possible to define Functional Requirements (FRs) for our product. The authors investigated a variety of concepts and considered them in the context of AD. It was quickly realized that there was an assumed coupling in the Customer Domain between a secure installation (CN_4) and having an operator interact with the live power line (CN_3,CN_7). The proposed concept that was able to eliminate this coupling was to make the sensor deployed by a drone and retrievable without additional intervention. This “temporary sensor” would achieve the same results without the need to install the sensor permanently. The goal is to create a self-detaching thermometer, inspiring the top-level “FR_0: Measure power line temperature for up to two weeks without service interruption” which is decomposed into:

- **FR_1** Logs data with 0.5 °C accuracy
- **FR_2** Discharges battery over two weeks of operation
- **FR_3** Deploys with the help of a drone within 10 minutes
- **FR_4** Survives a fall of 20 meters
- **FR_5** Removes itself from the line
- **FR_6** Transmits its data after usage
- **FR_7** Does not damage people or the power line

In addition to desired functionality, constraints were identified, though the exact tolerances were not known. Constraints come in two types[19, p. 21]: input constraints from the design specifications and system constraints that relate to the operating environment.

- **CON_1** Cost must be below X ISK. (Input)
CON$_2$ Survive extreme weather environments including thermal cycling, sub-zero temperatures, high-velocity wind, and precipitation in all formats. (System)

CON$_3$ Materials and components commercially available in Iceland. (Input)

CON$_4$ Measurement must not be affected by the strong electromagnetic field emitted by the alternating current high voltage transmission line. (System)

3. Concept Phase

These FRs led the team to the concept of a mobile temperature sensor that can be temporarily deployed and removed from live high voltage lines with the help of an external mechanism. Temperature readings from the conductors can be used in conjunction with LiDAR scans [20] of power infrastructure to optimize the allowable load on lines and predict the behavior of new power lines during the design phase. The device would deploy to the line with the assistance of a VTOL drone or other mechanism safe to use near high-voltage lines. Of note, LiDAR scans are already performed via a VTOL drone. The sensor would then log line temperature data over a predetermined period and fall off the line due to gravity at the end of this period. Multiple design elements need to be taken into consideration around high voltage lines suspended many meters up in the air.

The Information Axiom was considered for FR$_3$ and it was quickly realized that it might be very challenging for a drone pilot to line up an attachment area with the power line and trigger a clamp. A guiding rod and ramp geometry was added to orient the device with the line so that a drone can lower it onto a power line. A clamping assembly using an infrared reflection sensor triggers the device to start closing and an end stop indicates when the power line is secured.

There was also a concern about the robustness of temperature measurement. Data collection was handled with three digital thermometers for redundancy in case of error. These separate data streams can be evaluated together to check for corruption.

The Information Axiom guided the team to realize that there might be high information content on the release mechanism, so an additional effort was put into it. Customers indicated that even in the case of complete malfunction, it was critical for the device to end up on the ground to avoid service interruption while retrieving a faulty device. This resulted in a variety of fail-safe mechanisms that trigger on software, hardware, or battery failure: it is optimized to “Fail-open”. A real-time clock ensures proper timekeeping and triggers release upon matching the specified release time even if there is a period of low power.

3.1. Implementation

The chosen approach named “Line Dancer” was now ready for implementation. The PSs that were derived to fulfill the FRs are summarized by the top-level “PS$_0$: Self-attaching and self-detaching thermometer”

The subsequent PSs describe how the overall physical design should be implemented:

PS$_1$ Contact thermometer

PS$_2$ Compact battery with capacity at least 10000 mAh. Low power components drawing less than 100 mA

PS$_3$ Claw detects wire for attachment, guide rod

PS$_4$ Shock absorbent casing, Acrylonitrile styrene acrylate (ASA) filament for 3D printing

PS$_5$ Two independent mechanical/electrical fail-open emergency systems that detach unit in case of error

PS$_6$ Internals shielded for electromagnetism with metal lining. Redundant sensors for error correction

PS$_7$ Indicative safety through strong colors and warning noises.
The list of CNs, FRs, and PSs compiled into a CSDD diagram (Figure 2). Analysis of the CSDD indicates that this is an uncoupled system due to the lack of diagonal arrows. Metrics for FRs and PSs are used to check whether the prototype fulfills that element.

3.2. Concept Testing and Detailed Design
The next step in the process was concept testing where different deployment designs were shown to stakeholders. The clear preference from the stakeholders was deployment with a drone. The team decided to move forward with a design depicted in Figure 3a.

Next, a non-functional sketch model (Figure 3b) was created to gain a better understanding of how the unit would behave physically and the sizing of components. The prototype showed the need for an alignment rod and defined the boundary for the modules contained within.

3.3. Prototype
Based upon the CSDD, the team considered the appropriate modularization to build an integrated prototype. This prototype was intended to be a functioning proof of concept that would show the mechanisms without including the environmental hardening required for deployment in the field. The modules selected were:

**Chassis:** 3D printed housing, with shock-absorbent material particularly on the "head" which will be oriented down during release.

**Real Time Clock:** To ensure that the controller knows when it is time to release
Figure 3: Progression from sketch to model

(a) Sketch of selected concept: drone deployed
(b) Sketch model
(c) CAD model: Chassis overview and locking mechanism

**Micro Controller:** Adafruit Feather M0 Express Microcontrollers (Atmega SAMD ARM-based)

**Battery:** 10000 mAh LiPoly battery pack

**Sensor-Wire Clamp:** 3D printed transmission with DC Motor connected to worm drive

**Temperature Sensors and Attachment Module:** Multiple digital temperature sensors allow for detection of anomalies.

**Watchdog Module and Electrical Release:** To check if the main controller is functioning normally.

**Physical Release:** To force release via drone in case both sets of electronic fail.

The form of the final device was modeled in Autodesk Inventor 2022 (Figure 3c). The circuit diagram shown in Figure 4a shows how the components are wired together. To implement controller redundancy, two Adafruit feather microcontrollers were used. One acts as the main controller while the other one acts as a watchdog that triggers an emergency release routine when the main controller does not send a heartbeat signal for too long. A simple state machine and pseudo-code were used to guide what functionality the code needed to implement. The final version follows the control flow in Figure 4b.

The sensor-wire clamp and emergency release mechanism are pictured in Figure 5. The worm drive (threaded shaft) allows the clamp position to be maintained even when the motor is not powered. The spur gear is pressed against the worm drive by a monofilament fishing line holding the transmission together. The device releases from the power line via three independent ways:

(i) The main controller can reverse the clamp motor to open the clamp.
(ii) The watchdog controller can turn on a relay to a thermal wire to melt a polymer string that holds the clamp's transmission together. Once the transmission separates into two pieces, the clamp can move freely.
Figure 4: Line Dancer’s electronics and software design

Figure 5: Side view of clamp assembly. Monofilament fishing line keeps worm drive transmission engaged until it is melted or cut.

(iii) A drone can grab onto a hook on the alignment rod, which pulls a cutting blade against the polymer string to release the clamp (See bottom of Figure 6b).

The components were 3D printed using the model. The final prototype was then assembled from the components printed and modules build previously. The 3D printed components went through several iterations to optimize functionality. Figure 6 shows the final prototype in the two operational orientations.

4. Results and Discussion

Once the prototype was ready the team moved on to testing. An analytical prototype was developed in parallel with the physical one which both focused on the durability of the clamping mechanism to the power line. The prototype and accompanying tests had to confirm that the geometry was suitable for attaching the whole unit to the line. The device also needs to reorient...
Figure 6: The Line Dancer integrated prototype

(a) Deployment orientation highlighting electronics placement and impact absorption cap. Hooks on the end of the guide rod trigger the physical emergency release.

(b) Measurement orientation with closed attachment mechanism

when detaching to “land on its head” i.e. the shock absorber. Fail-safe detachment in case of software, hardware, or battery error also needed testing. Finally, the clamping force needed testing to prove that the device would stay securely on the line.

An important input into the analytical models was the mass of the system and its center of mass. The prototype weighs 954 grams. The center of mass is correctly placed to enable the Line Dancer to invert itself upon release of the clamp by pivoting around the wire: this is accomplished by positioning the center of mass high enough to create sufficient torque. The next prototype’s mass is likely to be heavier once metal shielding is incorporated into the casing for durability and magnetic field protection. This new mass will be used to calibrate the shock-absorber geometry for the next generation.

With the original cardboard sketch model, it was already possible to test out the physical geometries and specifications needed. The 3D printed physical prototype allowed us further testing whether the geometry and component selections were valid choices to meet the FRs. A basic FEA was performed with the analytical prototype which was derived from the CAD model of the suggested solution. The focus again was on the sensor to power line clamp. From the stress analysis (Figure 7), the design of the claw can withstand 80 N.

Subsequently, the team performed stress tests with the 3D printed physical model by attaching a force gauge to the device, while it was deployed to a metal rod and pulling until the device fell off. The unit detached under a load of approximately 25 N at which point the spur gear would slip against the worm gear. This force is significantly below the target value of 80 N and will require stiffer interfaces holding the worm drive against the spur gear; it is also possible this is a limitation of the 3D printed plastic.

The power consumption had to be analyzed to ensure that the device can operate for the desired interval of two weeks. The current usage could be found from data sheets of the various components and current measurements on the device. Battery capacity was generally listed in milliampere hours (mAh). Given the capacity of a battery and the current consumption, it was possible to calculate the battery discharge time through the relation \( t = C/I \) where \( t \) is time, \( C \) is capacity, and \( I \) is the current draw. Table 1 shows the calculations for the system at an idle state and maximum load. For the main apparatus, a 10000 mAh battery was chosen due to availability. The capacity in the deployment environment is likely to be lower due to lowered...
temperatures [21]. If the device spends most of its time running at the idle current consumption of 53 mA, this would result in 188 hours ≈ 7.8 days. This is lower than the session time of two weeks specified in FR2 but a reasonable measurement period because that the device can be retrieved, recharged, then redeployed again.

A future version will employ multiple strategies to meet FR2. The main controller will control a solid-state relay to cut power to the motor controllers and sensors during idle periods. The current battery can maintain the microcontrollers in idle mode for 666 hours ≈ 27.8 days, which would meet FR2’s duration. Idle periods will be increased to take measurements at 1-minute intervals or longer as the measurement session requires. Finally, the code will take advantage of the SAMD-based microcontrollers’ low-power modes to further reduce current draws.

An integration test was performed to evaluate the functionality of the system as a whole. A length of pipe the same diameter as a high voltage line was placed into the clamping area. The IR distance sensor was able to detect the “wire” and begin closing. If the wire was moved away before it finished closing, the clamp began opening. When the clamp completely closed, the end stop was triggered and the motor turned off. The device then measured the temperature on the line and was able to detach after a predetermined amount of time. Due to limited time, the prototype was not able to be tested with a drone deployment, but the prototype should be able to perform in the same way in such a situation.

At the stage of testing that was reached, temperature accuracy was secondary to the application of the device. The temperature sensors rated for 0.5 °C accuracy which is believed to be sufficient. The three separate measurements are processed by the microcontroller to generate a single temperature value even in the case of multiple sensors failing. Further testing is needed.
with these sensors in the presence of strong electromagnetic fields and to calibrate them with an official calibration thermometer.

4.1. Conclusion
The system dubbed “The LineDancer” can now successfully clamp to wire surrogates of various diameters in a controlled environment through manual placement. It can log temperatures even in the case of multiple sensor failures. Additional shielding is required to operate these sensors on a 220 kV powerline which will be addressed in future work. There are two fail-safe releases implemented in the Line Dancer, one physical and one electric. The physical release is triggered by an outside force and the electric one is triggered by the watchdog micro-controller. AD-driven design enabled the independent development of modules due to the FRs not being coupled.

The general design was able to measure temperature on a wire-like surrogate (FR0). The three digital thermometers with error correction ensure reliable measurement (FR1). The chosen LiPo battery does not currently meet the measurement duration but can be modified with less frequent measurements (FR2). Based upon automatic closing of the clamp in the integration experiments, drone deployment should be quick (FR3). The 3D-printed casing was not durable enough to survive a fall in its current iteration. Additional shock-absorbing material and a sturdier casing are in the works (FR4) FR5 was realized with a standard clamp release procedure and dual failsafe. The Adafruit Feather microcontrollers provide easy data extraction via USB or microSD (FR6) The warning signals, reflectors, and bright colors were unable to be realized in this phase of the project (FR7)

Overall, AD identified opportunities that became central to this product’s innovative aspects. We find that the current state of the project is a success. The prototype is not ready for production but highlights the benefits of a temporarily attached thermometer for line sag models. Overall the team believes that it has designed a unique product that has proved many key concepts it wanted to see working in action. Even with a very limited development cycle of 15 weeks, these results provide a springboard to further work in the area of high voltage engineering and drone-assisted measurement.

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