Reducing the Risk of Lithium-Ion Battery Fires

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***Abstract* - As the world rushes towards the use of "Green Technologies", power-dense Lithium-Ion Batteries (LIBs) are used everywhere, from small handheld devices to electric vehicles and autonomous naval platforms. LIBs will continue to play a crucial role in powering autonomous naval vehicles, increasing weapon energy storage, delivering quieter propulsion capabilities, and improving maneuverability and platform endurance. LIB cells have flammable electrolytes, which if damaged or incorrectly charged, can lead to high temperatures, toxic gas release, explosions, and fires. Several recent LIB-related ship fires have resulted in loss of life and significant financial losses. Increased LIB fire risk is due to several complex factors that aren't likely to improve anytime soon, such as: improper engineering, manufacturing, transporting, installation, charging/discharging, and storage. LIB fires are difficult to extinguish and often times reignite. While new rules and guidelines for addressing LIB fires are being developed by maritime regulatory authorities, the best practice is to prevent LIB fires from occurring in the first place.**

This paper describes new technology developed under Office of Naval Research funding for the early detection of thermal anomalies in shipboard electrical systems, including LIB storage areas and electric vehicles. The system uses state-of-the-art thermal cameras, coupled with advanced AI/ML software, to provide real-time thermal monitoring and alarm functions. The system detects and locates evolving hot spots before smoke and flame conditions occur. The system is scalable to hundreds of networked cameras, allowing for wide-area coverage typical of large ocean-going ships. Reducing the risk of LIB fires on ships is accomplished via early detection of thermal anomalies, triggering alarm notifications to initiate pre-emptive action to avoid fire. A comprehensive thermal alarm notification system interfaced to onboard fire suppression systems will allow maximum response time to thermal events, thereby improving safety to people, ships, and the environment.

Keywords—lithium-ion batteries, shipboard electrical, fire detection, fire prevention, thermal monitoring, machine learning, thermal runaway, fire suppression

I. Introduction

Lithium-Ion batteries (LIBs) have become increasingly popular over the past decades due to the need to provide energy solutions for power-hungry manned/unmanned vehicles and an assortment of advanced weapons systems. On the commercial side, LIBs power everything from electric cars, hybrid vehicles, and grid energy storage systems. LIBs have shown the most promise due to their power characteristics to meet stored energy requirements, but also due to their relatively small size and light weight. Their energy density is superior to other variations of batteries. However, a major concern about LIBs is their propensity for causing fires and exploding. LIB failure can cause the batteries to overheat, explode, emit toxic gases or experience a chaotic chain reaction called "thermal runaway".

This paper introduces a novel fire prevention system that can detect thermal anomalies in shipboard electrical systems in real-time and notify onboard fire suppression systems and appropriate authorities immediately, reducing the risk of loss of life and extravagant monetary and equipment losses. This system, called Infrared Monitoring System Advisor Functional Expert (IMSAFE), leverages the power of modern thermal cameras and AI technology to detect and locate hot spots before they lead to catastrophic consequences. Significant features of IMSAFE include:

- ability to extract high-resolution temperature data from state-of-the-art thermal cameras
- establishing a distributed network of large numbers of thermal cameras for wide-scale shipboard monitoring
- implementation of machine learning algorithms for thermal anomaly detection in electrical equipment, including LIBs
- development of an alarm notification subsystem to automatically activate shipboard fire suppression systems and alert crews

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Section 2 provides some background and covers the use of LIBs in contemporary commercial shipping and naval maritime applications. It also covers a brief recent history of LIB fires on ships. Section 3 discusses the construction of LIBs, their chemical description, and a description of a typical Battery Management System (BMS). The chain reaction that causes thermal runaway is discussed, as well as some canonical characteristics of LIB-induced fires. Section 4 provides an overview of the new IMSAFE system, including its embedded thermal monitoring technology, data management functionality, and its alarm notification subsystem. The integration of IMSAFE into a ship's fire suppression system is briefly discussed as well as an example of what this application could look like. Section 5 reports on some field experiments that were done where the system was deployed in an electric propulsion testing laboratory and aboard the R/V Neil Armstrong, a research vessel operated by the Woods Hole Oceanographic Institute.. Lastly, section 6 discusses an exciting future research avenue that we are exploring, including the use of fiber optic cables for electric equipment monitoring in small and hard-to-reach spaces.

II. Background

A. Navy & DOD Use of LIBs

LIBs are essential to thousands of military systems, from handheld radios to unmanned submersibles, as well as to future capabilities like advanced weapon systems and electric tactical vehicles. LIBs have a higher power density than other batteries, which means they can deliver more power per unit weight and volume, thereby increasing the endurance and range of the military platforms. Because of their importance, the Department of Defense (DoD) has developed the Lithium Battery Strategy 2023-2030 [1]. The strategy seeks to ensure that the military has the lithium-ion powered capabilities necessary for achieving National Defense Strategy objectives, including unmanned systems, directed energy capabilities, tactical vehicle electrification, dismounted warfighter communications, and distributed operations.

Other military applications where LIBs are being used or planned for use include emergency back-up power on ships, auxiliary power on aircraft, land-based directed energy weapons systems, UAVs, and depot storage of batteries used in soldier power systems.

Reliability and safety are critical concerns for advanced battery systems. Over-charged, degraded, or damaged LIBs emit hazardous gases that can cause explosions or mass fire casualty. Current battery monitoring methods, such as temperature and voltage, are insufficient for detecting impending battery failures with enough time to take mitigating action [2]. Better measurement tools and safer methods are needed to protect personnel and assets from potential fires and damage caused by LIB off-gassing.

B. Recent LIB Fires on Ships

With increasing use of LIBs, the associated risk of fires is also increasing for both commercial and naval ships. LIB fires can have disastrous consequences, causing damage to equipment and the ships themselves, resulting in large monetary costs. In the worst cases, these fires have resulted in injuries and even loss of life. LIB fires are often caused by thermal runaway, which we address in more detail in Section 3D. Some examples of the most devastating fires include:

- December 2023: fire was reported by the cargo vessel Genius Star XI while the ship was approaching Dutch Harbor, Alaska. The fire was out after days of burning. The ship was carrying LIBs from Vietnam to San Diego. The crew alerted the Coast Guard after pumping carbon dioxide into the hold where the blaze began and sealed it, fearing an explosion. The ship was kept 2 miles from shore to mitigate the risks of toxic gases while responders worked to extinguish the flames.
- November 2022: fire caused by thermal runaway of a lithium-ion cell within a handheld radio on the oil tanker S-Trust. The crew was able to extinguish the fire but it still resulted in over $3 million worth of damage (see figure 1).
- February 2022: the Felicity Ace caught fire and burned for over a week before recovery teams could board. The fire was suspected to be caused by a LIB in an electric vehicle. The ship sank, resulting in $500 million worth of damages (see figure 2).
- March 2021: the batteries of the Norwegian ferry Brim caught fire because of seawater/salt air intrusion. The late release of their fire extinguishing agent did little to stop the fire.
- June 2020: fire aboard the Hoegh Xiamen started while the ship was docked at the Horizon Terminal RO-RO facility. The fire burned for eight days, destroying its cargo of more than 2400 used vehicles worth $40 million. Nine firefighters were hurt fighting the fire.

C. Regulatory Activity by Maritime Authorities

LIBs are classified as dangerous goods and subject to strict transport regulations by maritime authorities around the world, including the International Maritime Organization (IMO), the European Union (EU), and the United States (US).

The IMO is the United Nations agency responsible for the safety and security of shipping and the prevention of marine pollution by ships. It issued the International Maritime Dangerous Goods (IMDG) Code [3], which sets out the rules and guidelines for the carriage of dangerous goods by sea. The IMDG Code classifies LIBs as Class 9 miscellaneous dangerous goods and specifies the numerous requirements for their transportation.

The EU regulates the transportation of LIBs by sea within its member states and with client countries. It adopts the IMDG Code as the basis for its legislation, but also adds some additional rules and requirements. The main EU legislation on the transportation of LIBs by sea is the Directive 2008/68/EC, which applies to the carriage of dangerous goods by road, rail, inland waterways, and by sea [4].

The US regulates the transportation of LIBs by sea within its territory and with foreign countries. It also adopts the IMDG Code as the basis for its regulations, but also adds some additional rules and requirements via the Department of Transportation's Hazardous Materials Regulations (HMR) under Title 49 of the Code of Federal Regulations (CFR) [5].

In addition to federal regulatory authority requirements, the major ship classification societies have also issued rules/guidance regarding the transport of LIBs.

- American Bureau of Shipping (ABS): ABS has issued a guide for the use of LIBs in the marine and offshore industries, which covers the design, installation, testing, and maintenance of LIB systems. The guide provides recommendations for fire protection, ventilation, and safety management. ABS follows the IMDG Code and the US HMR [6].
- Bureau Veritas (BV): BV has published a notation for the use of LIBs on board ships, which specifies the requirements for the design, installation, and protection of LIBs systems. The notation also defines the performance criteria and testing methods for the battery systems. BV follows the IMDG Code and the applicable national regulations.
- DNV GL: DNV GL has developed a set of rules and guidelines for the use of LIBs in maritime applications, which cover the design, installation, operation, and maintenance of LIB systems. DNV GL also follows the IMDG Code and the relevant regional and national regulations [7].
- Lloyd's Register (LR): LR has issued a service specification for the use of LIBS in ships and offshore units. The service specification also provides guidance on the risk assessment, fire protection, and emergency response measures for battery systems. LR also follows the IMDG Code and the appropriate local regulations.

Figure 1. S-Trust Oil Tanker Fire [8]

Figure 2. Felicity Ace RO-RO Fire [9]

III. Lithium-Ion Battery Description

A. LIB Design and Construction

Climate compliance and power requirements are often the most important factors that determine the type of battery chosen for integration in ships. However, there are other considerations when determining the appropriate battery type, such as whether it will be deployed for a continuous or periodic application or whether it is being used to power a primary power source or a secondary power source.

There are many key elements as detailed in Figure 3 to the construction of LIBs and determining the appropriate battery designs such as energy density, specific energy, selling price, cycle life, calendar life, temperature range, and fast charge. Other essential battery attributes to consider are capacity, voltage, discharge rate, depth of discharge and volumetric energy density.

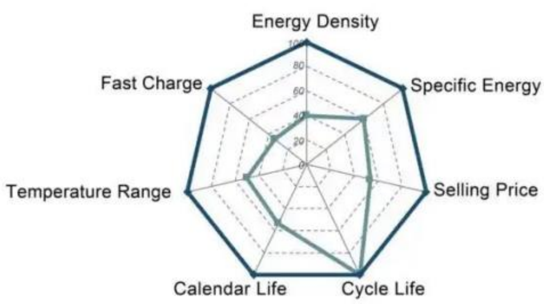


Figure 3. Battery Design Metrics [10]

The construction of a lithium-ion battery at its base is an anode, cathode, separator, electrolyte and two current collectors (positive and negative). The cathode and anode are where the lithium is stored, and the electrolyte carries positively charged lithium ions back and forth between the anode to the cathode. A good visual reference for the overall construction of LIBs is provided in Figure 4 [11].

B. BMS Description

A Battery Management System (BMS) prevents a cell from being overcharged or discharged. This can either be accomplished passively through the use of fuse-able materials or actively with integrated circuits, sensors, and interconnect hardware such as transistors, relays, and contactors. In addition to providing cell protection, a BMS may also be applied at the module and pack level. BMSs are often implemented in a 'Controller/Peripheral' architecture for larger installations where several module level BMSs are managed by a primary pack BMS.

Beyond basic protection, BMS are often able to provide State of Charge (SoC) and State of Health (SoH) estimations with varying accuracy. The more advanced systems leverage customized algorithms and feedback from temperature, voltage, internal resistance, and current sensors coupled with charge and discharge cycle data to establish a cell or battery's real time SoC and SoH. Figure 5 provides an overview of the functionality of a typical BMS. Given the many variables which can impact a battery's SoC, SoH and Remaining Useful Life (RUL), standard BMSs are not entirely accurate and are susceptible to drift error and must be regularly calibrated. Work is ongoing to improve the management algorithms with machine learning and to apply new, non-intrusive sensing technologies to more accurately capture a battery's SoC and SoH.

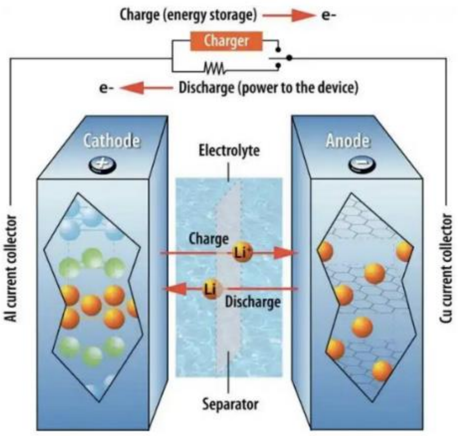


Figure 4. Lithium Ion Battery Construction [11]

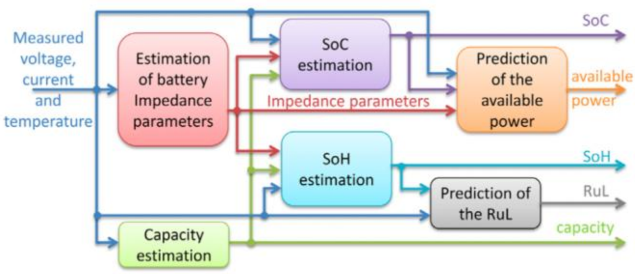


Figure 5. Functionality of Typical LIB BMS [12]

C. Evolution of Thermal Runaway

Thermal runaway denotes an uncontrolled escalation of temperature that causes a chemical reaction to occur inside the battery. The chemical reaction produces even more heat, which drives the temperature even higher, causing further chemical reactions. This often leads to severe repercussions such as fires, explosions, or rapid material degradation. Thermal runaway primarily ensues from the accrual of heat generated during routine operation or under adverse conditions such as overcharging, internal short circuits, or mechanical perturbations. Notably, this thermal runaway process in LIBs can be instigated by the breakdown of separator materials, precipitating direct electrode contact and ensuing exothermic reactions termed thermal events. These reactions precipitate accelerated heat release and gas production, fostering an amplification in temperature and internal pressure within the battery cell. Subsequently, escalating temperatures may cause electrolyte decomposition, further catalyzing the emission of flammable gases and exacerbating the thermal runaway trajectory. If unabated, thermal runaway may propagate rapidly across neighboring cells or battery modules, triggering a cascade effect characterized by rapid heat dissemination, flame propagation, and toxic gas emissions, thereby posing considerable hazards to nearby personnel and assets.

The time it takes for thermal runaway to occur depends on various factors, such as the battery type, the battery size, the battery condition, and the severity of the abuse. Thermal runaway can generally be classified into three types based on the time scale: fast, slow, and delayed.

- Fast thermal runaway occurs within seconds or minutes after the initiation of the abuse, such as short circuit, overcharge, or external heating. It is characterized by a rapid increase in temperature and pressure, leading to violent reactions, gas emissions, and fire or explosion.
- Slow thermal runaway occurs within hours or days after the initiation of the abuse. It is characterized by a gradual increase in temperature and pressure, leading to moderate reactions, gas emissions, and smoke or flame.
- Delayed thermal runaway occurs within weeks or months after the initiation of the abuse, such as self-discharge, parasitic load, or aging. It is characterized by a latent increase in temperature and pressure, leading to mild reactions, gas emissions, and heat generation.

Addressing the specter of thermal runaway within LIBs necessitates meticulous attention to design considerations, including the integration of robust thermal management systems, utilization of materials characterized by heightened thermal stability, and incorporation of safety mechanisms such as thermal cutoff devices or pressure relief vents. Adherence to optimal charging protocols and operational practices, coupled with routine maintenance and vigilant monitoring, assumes paramount importance in attenuating the likelihood of thermal runaway events and safeguarding the operational integrity of LIB systems.

D. Characteristics of LIB Fires

LIB fires have some signature characteristics. The most significant and dangerous feature being that they are extremely difficult to suppress. Central to these characteristics is the phenomenon of rapid ignition and extreme heat generation, owing to the batteries' elevated energy density. Upon ignition, these fires can escalate swiftly, intensifying their severity. Thermal runaway can precipitate the release of flammable gases, including hydrogen, carbon dioxide, and carbon monoxide, augmenting fire propagation dynamics and exacerbating hazards for responders. In instances of severe thermal runaway, the decomposition of battery electrolytes and internal components may culminate in explosive reactions, further heightening the fire's intensity and projecting hazardous debris. The combustion byproducts of LIB fires encompass toxic fumes and smoke, comprising substances such as lithium oxide and lithium fluoride, thus posing health risks to firefighting personnel and bystanders alike. The risk of re-ignition post-suppression efforts persists, particularly if battery cells remain thermally elevated or undergo renewed thermal runaway. LIB fires present formidable challenges to conventional suppression techniques, necessitating the deployment of specialized extinguishing agents and protocols. The potential for thermal runaway propagation across multiple battery cells or modules underscores the importance of preemptive strategies, such as enhanced real-time thermal monitoring with predictive capabilities.

E. Reducing Fire Risk with Enhanced Monitoring

In the context of ship transport of electric vehicles, thermal cameras can reduce the risk of electric vehicle fires by providing early detection of heat sources and potential fire hazards [12]. They can detect heat signatures and temperature variations, allowing them to identify hotspots or overheating components. By detecting these anomalies early on, thermal cameras can alert the crew to potential fire risks before they escalate into full-blown fires. The crew can then take immediate action to address the problem to prevent a fire from occurring.

Thermal cameras can also provide enhanced visibility in low-light or smoky conditions, making it easier for the crew to locate fire sources or hotspots. This can be particularly useful in cargo areas where electric vehicles are stored, as it allows the crew to quickly identify any signs of overheating or fire. Thermal cameras can improve the safety of crew members by allowing them to monitor the temperature anomalies from a safe distance. This reduces the risk of exposure to high-voltage components or toxic gases that may be released during a fire.

IV. IMSAFE Overview

IMSAFE (Infrared Monitoring System Advisor Functional Expert) is a fire prevention system jointly developed by PacMar Technologies and MACSEA Ltd. The system is designed to prevent fires and other catastrophic failures through the early detection of thermal-related anomalies. It utilizes thermal cameras, Artificial Intelligence (AI) and Machine Learning (ML) algorithms, and COTS hardware to provide real-time thermal monitoring of electrical equipment, including electrical vehicles with LIBs. The system uses an Ethernet-based network of infrared cameras that can monitor both small and large spaces containing electrical equipment, machinery, and high-energy batteries. These cameras capture both thermal images and temperature readings, allowing for the detection of thermal anomalies and analysis of heat progression. The system is scalable and can be used with anywhere from 1 to hundreds of cameras, depending on the size and requirements of the monitored area. A typical 3-camera configuration is shown in figure 9. IMSAFE can be readily integrated into existing machinery spaces and alarm automation systems.

IMSAFE offers several benefits, including:

- Early identification of localized hot spots.
- Automatic activation of fire suppression systems.
- Ability to view thermal images in alarm to help crew assess an evolving situation.
- Increased safety of crew, ship, and firefighters with continuous, real-time monitoring of LIB health.
- Straightforward integration with existing alarm and monitoring systems, including fire suppression equipment.

A. Thermal Monitoring Technology

There are a large number of infrared cameras on the market from which to choose. The IMSAFE prototype is based on well-proven, state-of-the-art FLIR/Teledyne smart sensor camera technology [13]. Specifically, the thermal camera allows the capture of both thermal images and temperature measurement data. The camera’s infrared resolution (464 X 348 pixels) provides 161,472 individual temperature measurements per thermal image captured (i.e., one measurement for each pixel). Table 1 provides some additional specifications for the thermal camera.

Table 1 – Thermal Camera Specifications [13]

Parameter	Specification
IR resolution	464 X 348 pixels
Detector pitch	17 µm
Spectral range	7.5 – 14.0 µm
Detector type	Uncooled microbolometer
Dynamic range	16-bit
Frame rate	30 Hz
Standard temp range	-20 °C – 175 °C; 175 °C – 1000 °C
Focus	adjustable

B. Camera Data Management

Representing each of the 161,472 temperature measurements (pixels) as a floating-point data type in computer code requires 645,888 bytes of memory per image. With three cameras running simultaneously, approximately 2MB of memory is captured during each camera image data sample. With a 30-second camera sampling rate, approximately 5.6 GB of data storage per day is required to be managed. For faster sampling rates, or with more than three cameras, data management becomes a hurdle for real-time processing.

IMSAFE implements a data management scheme to drastically reduce the size of data that must be held in memory and stored to disk. Recording 161,472 floating point temperature values for each camera per sampling interval is non-optimal. Most temperature values will not change if the electrical component being monitored by the camera is in steady state. The recorded data will be uninteresting and data management will strain system resources over time.

An improved approach was developed whereby only temperature data that has increased beyond a specified threshold over ambient temperature from the previous camera sample is stored in a database. Instead of monitoring "raw" temperature measurements, IMSAFE tracks deviation from ambient temperature for all pixels associated with a given image. Ambient temperature values can be read from each camera. Temperature rise values, "TempRise", are then computed for each pixel as the change from the current image sample compared to the previous image sample. A configurable thresholding function then determines if the corresponding pixel-based temperature data should be recorded. A TempRise value, along with its pixel Identification, is only recorded if it exceeds a pre-defined threshold. If nothing is changing in the camera's field of view, no data is recorded. This approach results in a drastically smaller number of records written to the database.

Storing large amounts of acquired temperature data in a typical relational database can be problematic. Our testing revealed that a traditional transactional SQL database server (e.g. MySQL) could not satisfy camera data management requirements. It became too slow and eventually unresponsive as the volume of data grew. An investigation into special-purpose Time Series Database (TSDB) packages was then undertaken.

A TSDB is a specialized database system designed specifically for efficiently storing, querying, and analyzing time-stamped data. These databases are popular for applications where data points are collected and recorded over time, such as IoT sensor data, financial market data, and real-time data monitoring systems. We experimented with several TSDB packages and found them to perform well. For example, one test was conducted over a three-day period and involved three thermal cameras mounted on tripods pointing out our office windows onto a busy street. Changing ambient light levels, pedestrian traffic, and vehicle traffic created dynamic conditions which triggered the cameras to record data. The camera sampling rates were set to 10 seconds and a Temperature Rise Threshold of 1 ^{o}F was configured. The system ran successfully over the 3-day test period with the following results:

- 14,610 thermal images were recorded,
- 4.3 billion TSDB records were recorded, and
- The TSDB required approximately 116 GB of disk space.

C. Alarming Notification Subsystem

As illustrated in figure 6, IMSAFE can issue control signals to trigger external systems (e.g., fire suppression, etc.) It also generates alarm log records to disk and can send email and text message alerts to responders, The prototype system employs threshold alarming, but future versions will include more sophisticated statistical and AI-based alarm methods. For example, statistical trending analysis can issue predictive alarms when increasing temperature trends are detected., providing the earliest warning possible.

D. Integration into Fire Suppression System

IMSAFE acts as a TCP/IP server such that standard Ethernet server-client communications are used issue control signals to one or more external clients (see figure 7).

V. Field Trials

Field trials consisted primarily of land-based laboratory testing where controlled LIB experiments focused on the generation of thermal images for machine learning of thermal anomalies in the battery stack. In addition, at-sea trials of IMSAFE were conducted onboard a research vessel to test system operability under real-world conditions.

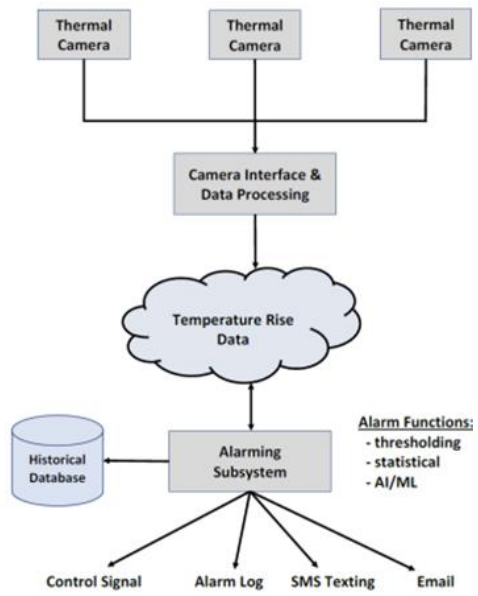


Figure 6. Functionality of a Three-camera System

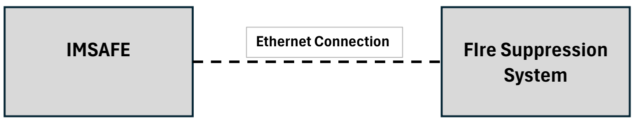
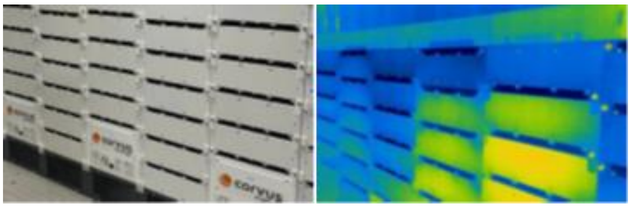


Figure 7. IMSAFE – Fire Suppression System Interface

A. Electric Propulsion Laboratory

PacMar maintains an electric propulsion (EP) testbed laboratory in Portland, ME. to prove different electric propulsion components and related control technologies. The testbed has four electric motors installed on a single shaft that can produce 375 hp of continuous shaft power, with up to 1,000 HP boost. Power to the testbed is supplied by an external 271 kWh Lithium-Ion Corvus Orca battery bank isolated in a climate controlled 20' CONEX box. As shown in figure 8 below, the ability to control LIB temperature within safe limits allowed thermal image datasets to be captured for training LIB fault classification machine learning models.



(a) (b)

Figure 8. (a) LIB Battery Stack, (b) LIB Thermal Image

A three-camera packaged system (cameras with shipboard controller, power supply, and networking connections) is shown in Figure 9 and was used to experiment with LIB-based electric vehicles in the EP laboratory. Figure 10 shows two tripod-mounted thermal cameras, as well as one supported by a custom mount placed under the front of the EV. The lower right inset of figure 10 shows the thermal images from each camera.

Figure 9. 3-Camera IMSAFE Packaged System

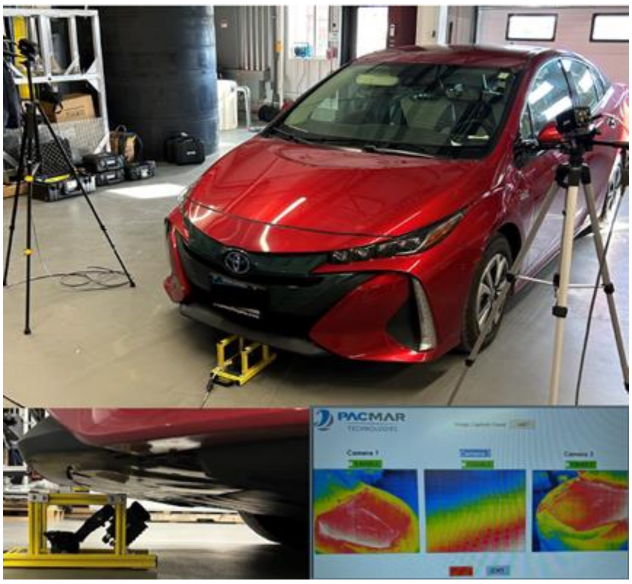


Figure 10. EV Testing at PacMar EP Laboratory

B. R/V Neil Armstrong Operational Testing

A six-camera IMSAFE system was tested during a 5-day offshore cruise in November 2023 on the Woods Hole Oceanographic Institute (WHOI) R/V Neil Armstrong (see figure 11). The system was installed to thermally monitor various mechanical and electrical equipment in the diesel-electric engine room.

Figure 11. Test Vessel - WHOI R/V Neil Armstrong

After the cruise, a review of IMSAFE data revealed that over a hundred thousand images and over one billion data points were recorded. Several thermal test images from the different IMSAFE testing activities are shown in Figure 12.

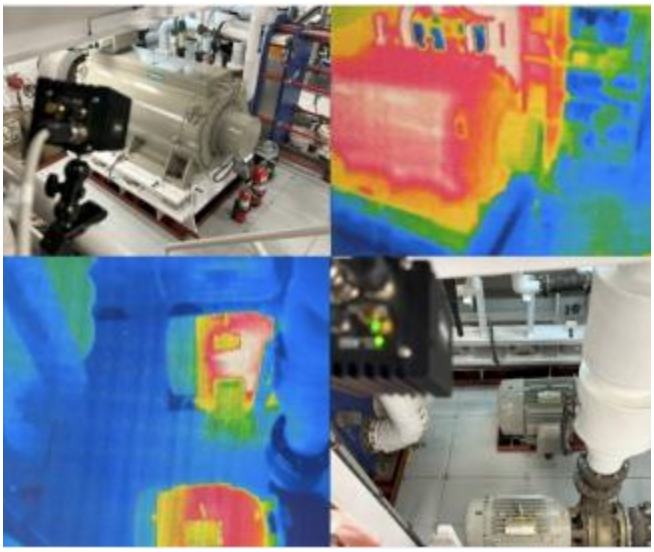


Figure 12. Test images from the R/V Neil Armstrong

VI. Future Research and Development

A. Fiber Optic Cables

One promising research avenue involves the use of Infrared (IR) fiber optic cables for thermally monitoring hard-to-see and space-constrained equipment. In the pursuit of facilitating thermal monitoring within a rugged and distributed shipboard application, our research team is exploring the use of IR fiber optic cables for the transmission of heat from physically distributed components to a centralized patch panel, as depicted in figure 13.

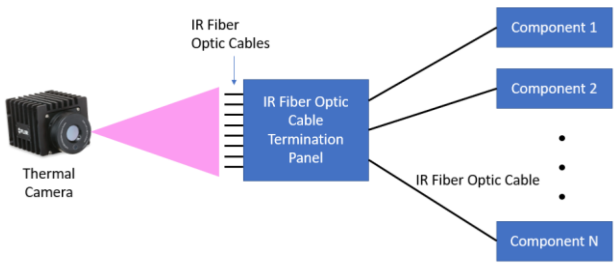


Figure 13. Thermal Sensing with IR Fiber Optic Cables

Under this framework, a solitary thermal camera would oversee multiple equipment health from this designated patch panel. Wien's displacement law can be used to estimate the surface temperature of objects by discerning the peak wavelength or frequency of their thermal emission spectrum. Formally expressed, Wien's law is articulated as follows:

$$\lambda_{max} = \frac{b}{T} \quad (1)$$

where λ_{max} = peak wavelength of light (mm),
$b = 2.8977719\ mm - K$ (Wiens displacement constant), and
T = surface temperature (°Kelvin).

Typically, on shipboard electrical equipment, the expected operating temperatures result in emitted light wavelengths between 0 and 10 µm. Suitable IR fiber optic cables could then be selected to match/sense IR energy within this bandwidth.

To validate the use of IR fiber optic cables, IR cables of varying diameters were obtained for physical testing. A simple feasibility test was conducted to determine their viability before beginning more formal testing with representative shipboard electrical equipment. For the feasibility test, one end of each cable was held close to a heat source and the other secured to a tripod holding a thermal camera. Figure 14 shows the light emitted from the non-heat source end of the cable (light end of cable is circled for clarification). One end of each cable was connected to a patch panel located in front of a thermal camera (see Figure 15) while the other ends were placed close to various electrical heat sources. An image of one cable transmitting thermal radiation from the inside of an electrical enclosure is shown Figure 16. Limited testing showed the effectiveness of IR fiber optic cables to transmit thermal radiation from electrical components for monitoring by a thermal camera. Additional research is required to fully vet this technology for military shipboard use.

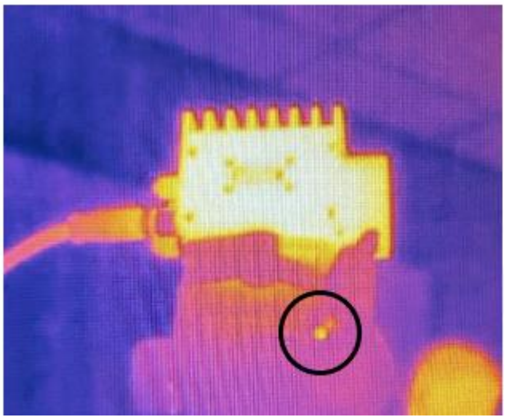


Figure 14. IR Fiber Optic Cable Light Source

VII. Conclusions

Lithium-Ion batteries have become increasingly popular because they provide energy solutions for a diverse range of consumer devices and military equipment, including many evolving manned and unmanned vehicles, as well as assortment of advanced weapons systems. However, a major concern about LIBs is their propensity for causing fires and exploding. LIB failure can cause the batteries to overheat, explode, emit toxic gases, and experience a chaotic chain reaction called thermal runaway. Entire ships and lives have been lost due to LIB thermal runaway. LIB fires are difficult to extinguish and often times reignite.

Increased LIB fire risk is due to several complex factors that aren’t likely to improve anytime soon, such as: improper engineering, manufacturing, transporting, installation, charging/discharging, and storage. While new

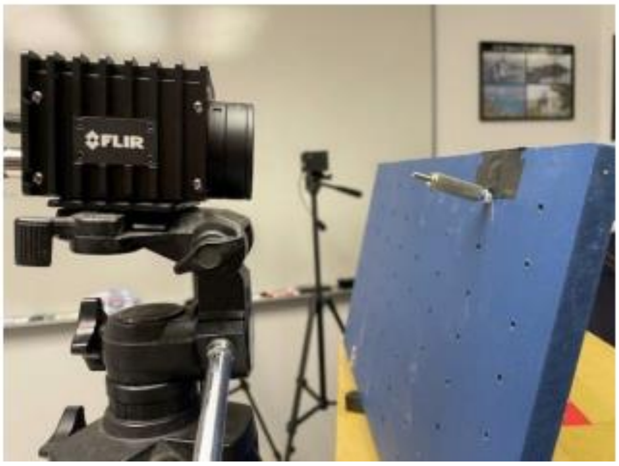


Figure 15. IR Cable installed in a patch panel.

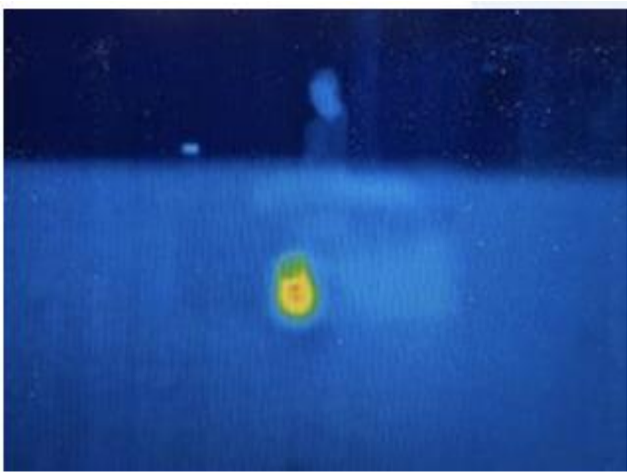


Figure 16. Thermal image of a cable showing a heat source at 124.2 °C.

rules and guidelines for addressing LIB fires are being developed by maritime regulatory authorities, the best practice is to prevent LIB fires from occurring in the first place.

Reducing the risk of LIB fires on ships can be accomplished via early detection of thermal anomalies, triggering alarm notifications to people and automation systems that trigger pre-emptive action to avoid fire. We have presented new technology for this very purpose that uses state-of-the-art thermal cameras, coupled with advanced AI/ML software, to provide real-time thermal monitoring and alarm functions. The system detects and locates evolving hot spots before smoke and flame conditions occur. The system is scalable to hundreds of networked cameras, allowing for wide-area coverage typical of large ocean-going ships. A comprehensive thermal alarm notification system interfaced to onboard fire suppression systems will allow maximum response time to thermal events, thereby improving safety to people, ships, and the environment.

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