Approaches for Enhancement of Perception Through Sensor Design for Extreme Environment

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***Abstract*—The application of artificial intelligence (AI) and robotics in extreme environments, is crucial for addressing complex challenges and performing high risk tasks. We highlight the importance of multi-modal sensor redundancy to ensure system reliability and accuracy despite sensor failures caused by harsh environmental conditions. We propose design considerations for sensors in extreme environments, emphasizing both the hardware and software design. One method is the non-contact heart rate and temperature monitoring using RGB visible and infrared cameras. This method addresses the limitations of traditional visible light sensors under complex illumination conditions, enhancing data reliability through advanced data fusion techniques. Furthermore, we propose a panoramic sensor lens design with a 270-degree view for comprehensive environmental perception, reducing mechanical vulnerabilities. These designs demonstrate the effectiveness of combining infrared and visible light sensors for improved environmental perception and physiological monitoring.**

Keywords—Mechanisms, Design, and Control, Vision and Sensor-Based Control, Visual Perception and Learning

I. INTRODUCTION

The application of artificial intelligence (AI) and robotics in extreme environments is crucial for tackling complex problems and performing high-risk tasks. These environments include deep oceans, outer space, polar regions, volcanic craters, and nuclear reactors. By leveraging AI and robotics, it is possible to enhance the capability and safety of operations in extreme environments, providing reliable and precise performance.

There are some key aspects of AI and robotics applications in extreme challenging conditions including autonomous navigation and obstacle avoidance, environmental perception and data fusion, self-diagnosis and repair and task planning and decision support. Sensors provide critical data that enable systems to understand and interact with their surroundings. Sensors will be fundamental in these applications.

In extreme environments, a single sensor may fail due to harsh conditions such as extreme temperatures, high radiation levels, or severe physical impacts. This vulnerability can compromise the reliability and accuracy of the entire system.

To mitigate this risk, multi-modal redundancy is employed, integrating data from various sensor types—such as infrared, visible light cameras, LiDAR, and sonar—allowing for cross-verification and ensuring continuous operation. This approach enhances system robustness and reliability, providing a comprehensive and resilient understanding of the environment, which is crucial for applications in autonomous vehicles, space exploration, and disaster response.

In this paper, we propose design considerations for sensors in extreme environments, emphasizing both the hardware and software design. Non-contact heart rate with Remote Photoplethysmography (rPPG) technology and temperature monitoring using RGB visible and infrared cameras. This method addresses the limitations of traditional visible light sensors under complex illumination conditions, enhancing data reliability through advanced data fusion techniques. Furthermore, we propose a panoramic sensor design with a 270-degree view for comprehensive environmental perception, reducing mechanical vulnerabilities.

II. RELATED WORK

There are several key aspects of AI and robotics applications in extreme challenging conditions. For example, sensors may fail in extreme conditions. Multi-modal sensor data fusion is particularly important in extreme environments. AI algorithms can process data from infrared, visible light, LiDAR, and other sensors to provide accurate and comprehensive environmental perception. The robotic equipment in extreme environments is prone to damage. The mechanical structure maybe vulnerable. Hardware design should avoid the complex mechanical structure. AI technology should monitor the status of robots in real-time, predict faults, and perform self-diagnosis and repair, thereby enhancing system reliability. Tasks in extreme environments are often complex and dynamic, requiring real-time adjustments. AI can use reinforcement learning and optimization algorithms to analyse environmental changes, adjust task planning, and provide decision support.

Robotic system through multi-modal redundancy, utilize various types of sensors and data sources to enhance system reliability. By incorporating redundancy from multiple sensors, the system can cross-verify information, mitigate the risk of single-point failures, and ensure more robust and accurate performance even in challenging and extreme environments.

Space is a typical extreme environment. Zhang *et a*l. [1] reviewed the significant advancements in soft robotics and their potential applications in space in recent years, focusing on design and modeling, fabrication, sensing, and control. They discussed the unique design requirements intended for space by analyzing the characteristics of the environment and the specific needs of missions in space.

Astronaut body state sensors are essential for monitoring their physiological parameters and health status to ensure their safety and well-being in space. These sensors can detect and monitor various physiological indicators, including heart rate (HR), head temperature, blood pressure, respiratory rate and so on. These sensors are typically integrated into spacesuits or wearable devices to continuously monitor the astronauts' health during space missions. The data is transmitted in real-time to ground control centres, where doctors and experts can perform remote diagnostics and interventions based on the information received. Heart rate is one of the most crucial physiological indicators for human being, providing significant insight into an individual's physical health. We propose to get the heart rate and temperature information estimation with RGB visible and infrared camera.

The non-contact measurement method with cameras has become an increasingly significant field of research It has been used for contactless information collection [2-4]. In space, complex illumination conditions significantly impact visible light signals, which can affect imaging and data acquisition systems. These conditions include extreme variations in light intensity, harsh shadows, and the presence of direct and reflected sunlight.

Augmenting visible light sensors with infrared sensors can enhance system reliability and performance. Integrate data from visible light and infrared sensors using advanced algorithms to generate comprehensive environmental perception data. This will enhance the accuracy and reliability of the data. It provides multi-angle and multi-spectral information, improving detection capabilities.

Correa *et al.* [5] introduce a robot equipped with an infrared camera to detect humans and an optical camera to capture video of the scene. Accurate human detection is accomplished by integrating thermal and visual information sources to identify human-like objects. These objects are then further processed to verify the real presence of humans and determine their identity using facial information from both thermal and visual signals. Face detection confirms the presence of humans, while face recognition identifies them.

Thermal camera can be used in inspection of the robotics itself. Nikolas Theissen [6] proposes a thermal compensation approach for articulated robots based on the joint power consumption. This work focuses on modeling, measuring, and identifying changes in the kinematic chain of serial articulated robots caused by thermo-mechanical deformations due to self-heating. Thermal sensing is performed using a FLIR SC640 infrared camera.

The utilization of rPPG technology for remote heart rate monitoring is an increasingly significant filed of research recently. Many conventional methods have been implemented including Blind source separation (BSS), CHROM, PBV, Spatial Subspace Rotation, POS etc [7-17].

But there are still various influencing factors such as complex illumination conditions need to be addressed to enhance the performance of rPPG methods to real-world application standards. Visible cameras are susceptible to on-site environmental disturbances, such as complex illumination conditions. The infrared sensor/camera would overcome these problems. Temperature of the face region is usually different from the ambient environment. Therefore, temperature signal from IR camera can be used to verify the correct face region. Region of interest (ROI), skin segmentation is used to extract the skin region that can be used to calculate the pulse rate.

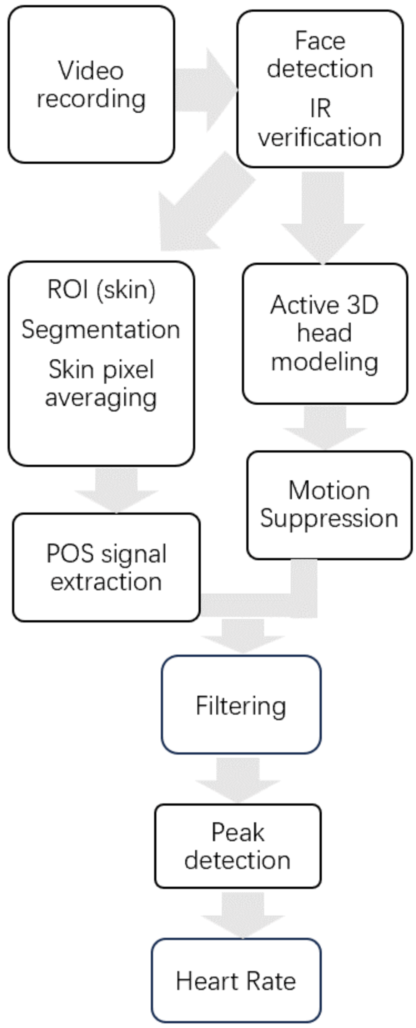

Fig. 1 The process flow of our proposed method

In extreme environments, rotating mechanisms for panoramic scanning are susceptible to damage from factors like extreme temperatures, high radiation, dust, and physical impacts. These harsh conditions can lead to mechanical wear, corrosion, or part failures, affecting the sensor system's reliability and accuracy. To overcome these challenges, it is crucial to design robust and durable rotational systems. Alternatively, non-mechanical solutions such as electronic beam steering or using multiple fixed sensors can be considered to avoid the risks associated with mechanical rotation. These methods ensure continuous and reliable panoramic data acquisition, which is vital for applications in space exploration, autonomous vehicles, and other extreme settings. Additionally, we propose using a super wide-angle sensor with a 270-degree view as an alternative to rotational systems in extreme environments.

III. Methods

A. Non-contact heart rate and temperature monitoring using dual cameras

The process flow of our proposed non-contact heart rate and temperature monitoring using RGB visible and infrared cameras method is shown in Figure 1.

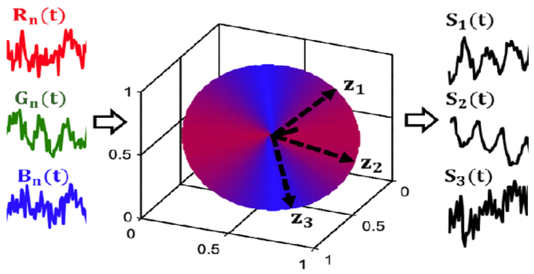

Fig.2. Pulsatile strength distribution on the plane orthogonal to (1,1,1) T. Redesigned from [10]

Plane-Orthogonal-to-Skin (POS) [10] algorithm proposes a plane that is orthogonal to the skin tone in the temporally normalized RGB space to extract the pulse. In the RGB space, skin tone can be represented as a specific color vector. The skin tone generally has a specific distribution range although it varies among individuals and under different lighting conditions. This algorithm can effectively separate the color changes due to blood flow from those due to other factors. POS obtains the overall excellent performance among model-based methods. In this work we use POS algorithm for heart rate estimation.

The cameras start to record the video information. Then face detection algorithm is implemented to segment the face from the video. Temperature of the face region is usually different from the ambient environment. Therefore, temperature signal from IR camera can be used to verify the correct face region. Region of interest (ROI), skin segmentation is used to extract the skin region that can be used to calculate the pulse rate. Skin pixel averaging and POS algorithms are implemented for signal extraction. The movement of the head must be considered. Therefore, the active 3D head modelling motion suppression algorithms are implemented at the same time. The final combined signal is filtered to detect the peak. The heart rate is calculated.

The calculation is as below:

Face detection:

Initially, the face area is detected and captured by the RGB camera. The actual face area used for calculations is a combination of two regions: (a) the cheek area between eyes and jaw, and (b) the region around the nose.

We can use OpenCV for face detection and rPPG algorithm to get the body signals.

OpenCV already includes many pre-trained classifiers for detecting faces, eyes, emotions, and more. We use the face classifier in this work.

A conversion matrix between the thermal infrared camera and the visual camera was utilized to combines the coordinate system between the dual cameras into one common coordinate frame.

POS algorithm

POS algorithm is designed targeting certain applications and effects. The key point is defining two projection axes on the plane that can encompass the most likely pulsatile region.

In this section, time is denoted by t. Transposition is denoted by T. Vectors and matrices are denoted as boldface characters. The column vectors are denoted as **v**. Fig. 2 shows the pulsatile strength distribution on the plane orthogonal to (1,1,1) as a function of **z**. The projection plane consists of 360 discrete projection axes, each sampled with a 1° difference. In this representation, red denotes regions with stronger pulsatile strength, while blue indicates regions with weaker pulsatile strength.

A temporally normalized RGB signal Cn (t) = [Rn (t), Gn (t), Bn (t)] can be projected onto **z1, z2, z3** and obtain **S1 (t), S2 (t), S3 (t).**

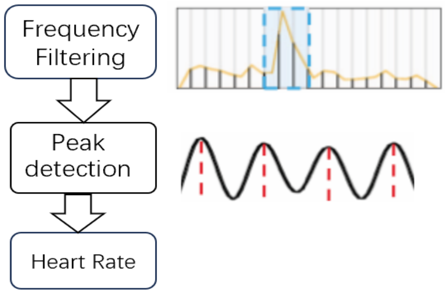

Fig.3. Heart rate estimation after signal extraction and fusion

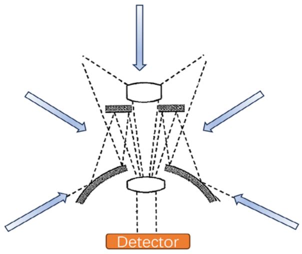

Fig.4 The total field of view is approximately 270 degrees in the entire 360-degree periphery

For example, three projection axes are on the plane: **z1** = $[-2, 1, 1]^T$, **z2** = $[1, -2, 1]^T$, and **z3** = $[1, 1, -2]^T$ as shown in Figure 2. They have the pulsatilities −0.64, 0.68, and −0.04, respectively.

POS algorithm computes in the following steps:

1) Spatial averaging
2) Temporal normalization
3) Projection
4) Tuning
5) Overlap-adding

Heart Rate Estimation

In the previous steps we got the heart rate signal. Now we estimate heart rate from the signal with peak detection. To refine the signal for further peak detection, it is typically interpolated using a cubic spline function. Peaks can then be easily identified as the maxima within the signal using a moving window. The method is shown in Fig 3.

By using individual peaks, it is possible to extract additional information, such as heart rate and respiration rate variability, from the inter-beat intervals.

B. 270 degrees view sensor lens for extreme environment.

To obtain a panoramic view, rotational scanning is employed, where the sensor or camera system rotates to capture images or data from multiple angles. This method involves systematically turning the sensor around its axis, collecting a series of overlapping images or data points that cover the entire surrounding environment. These individual captures are then stitched together using specialized software to create a seamless panoramic image or a comprehensive 3D map.

In extreme environments, rotational structures used for panoramic scanning can be prone to damage due to harsh conditions such as extreme temperatures, high radiation levels, dust, and physical impacts. These conditions can cause mechanical wear,

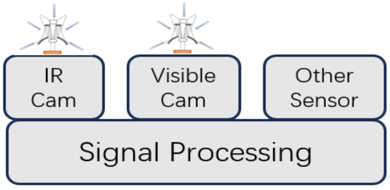

Fig.5 The design of multi-sensor board for robotics perception

corrosion, or failure of moving parts, compromising the reliability and accuracy of the sensor system. To address these challenges, it is essential to design robust and durable rotational mechanisms. Additionally, non-mechanical alternatives like electronic beam steering or the use of multiple fixed sensors can be explored to mitigate the risks associated with mechanical rotation. Such approaches ensure continuous and reliable panoramic data acquisition, critical for applications in space exploration, autonomous vehicles, and other extreme environments. We can also use super wide angle sensor design to take the place of the rotational system. We propose sensor with 270 degrees view lens for extreme environment.

This proposed system offers a total field of view that is approximately 270 ° vertically (in the forward direction) in the entire 360-degree periphery." It provides matched magnification between the forward and panoramic images, creating seamless boundaries without overlap or blind spots. [18].

This design provides an ultra-wide field of view, including rear-view capabilities, without relying on moving parts like panning and tilting mechanisms. Unlike fisheye lenses, which suffer from significant distortion due to uneven light refraction, this design minimizes distortion and ensures a clearer image. Traditional panoramic imaging systems often can't capture the entire front hemisphere, and existing reflector systems only offer peripheral views without forward imaging. Pan and tilt systems can cover the same field of view but require mechanical movement and cannot display the entire field of view simultaneously on the image plane. This new design addresses these issues, making it ideal for applications in extreme environment.

This field of view is produced by integrating the forward and panoramic fields of view onto a single image plane. These views are seamlessly connected without any gaps or blind spots. The boundaries between the forward and panoramic views are nearly parallel, gently converging to overlap slightly. The forward view covers approximately 80 °, while the panoramic view extends about 95 °, covering 50 °and 45 °above and below the horizon, respectively. The magnifications are designed to be matched between the forward and panoramic views, resulting in a continuous image with uniform brightness and size. The distortion at the boundaries are eliminated by optical path design.

The detector can be either visible or infrared detector. For infrared detection, the optical system can be optimized for use with an infrared imaging sensor, such as uncooled microbolometers, thermopile arrays or focal plane arrays, for thermal or far-infrared imaging application. Due to the wavelength differences in the optical signals being transmitted, different materials with specific properties for certain wavelengths are required. For instance, gold coatings are used for IR reflectors as they are standard for IR reflective coatings. The selection of materials for the optical parts in the imaging and focusing lens group can include Zinc Selenide, Sodium Chloride, and Cesium Bromide. The system can also be optimized to match the size and resolution of the sensing chip.

For the space application, we propose the multi-sensor board for robotics perception as shown in Figure 5. Both infrared sensor and visible imaging sensor are mounted to get the signal with different

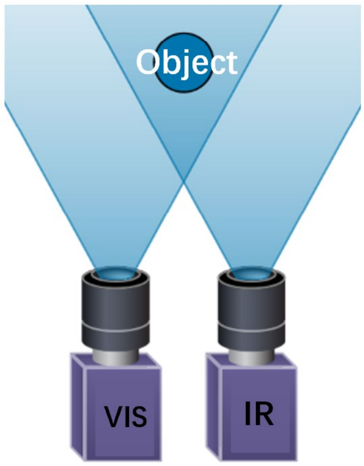

Fig.6. Stereo vision system combining an infrared imaging sensor with a visible camera

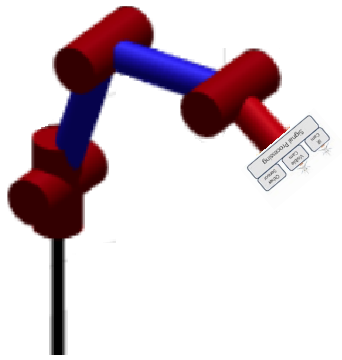

Fig.7. Design of 4-Degree of Freedom robotic arm with proposed multi-sensor board

optical spectrum. There is also space for integrating other sensors such as LiDAR, and sonar. Different sensors can share the common signal processing block for lowering power and reducing system complexity. By integrating data from various sensor types—infrared, visible light cameras, LiDAR, and sonar—systems can achieve robust performance through cross-verification and continuous operation.

These systems can offer extremely wide, continuous fields of view. The systems are suitable for both interior and exterior sensing applications. They can be mounted in a forward position, on the ceiling, or on an upright post for different applications. The systems can be integrated with imaging or motion analysis software for further applications, including but not limited to motion detection, fire detection and so on.

C. More applications

Smart

It is crucial to explore the synergistic combinations of various types of sensors other than their standalone capabilities. The integration of various sensors embedded in robotic systems provides high-quality information and significantly enhances robotic perception. The system can be smarter.

The visible cameras can also be used to compute the distance with high accuracy.

Stereo vision is a technique that uses two cameras positioned at different angles to capture the same scene. By comparing the differences (disparities) between the two images, it calculates the distance to objects in the scene. Combining an infrared camera or imaging sensor with a visible light camera to create a stereo vision system involves utilizing the different properties of the two types of cameras to enhance depth perception and improve measurement accuracy, especially in environments with varying lighting conditions. A stereo vision system combining a visible and an infrared camera is shown in figure 6.

We can also explore the optical tactile sensor applications in space for griper operations.

Another example is provided in article [19], which proposes a system that combines facial recognition with audio-lingual emotion recognition. This approach would enhance task performance and help the robot establish a stronger connection with the operator.

Service

Autonomous maintenance is important in the space. The sensor on robotics itself can be used to check the status. For example, the visible camera can provide detection of defects of the system. The IR sensor can be used to check the abnormal thermal signals during the operation and maintenance process.

The proposed multi-sensor board can be mounted on a robotic arm with 4 or more degrees of freedom. Then the sensors can be used for check the space ship or vehicles.

It can also be used as vision system for navigation. In extreme environments, GPS signals may be unavailable, and the terrain can be highly variable. Traditional navigation systems may struggle to adapt. AI technologies, through machine learning and deep learning algorithms, can analyse sensor data, generate environmental maps, and enable autonomous navigation and obstacle avoidance. This multi-sensor board with super wide field of view is helpful to gather environmental information for further processing.

IV. Results and Discussion

There are several facts could infect the result including skin tone, luminance, movement, etc. Although we already use filter and projection methods to minimize these effects, but we still cannot ignore them. The IR camera helps to identify the skin region on face by measuring the temperature on the face. The face detection by visible camera will make the extraction and calculation of temperature more accurate. Because the calibration of IR is more accurate with the accurate face area.

We did many tests by comparison with apple watch's ECG, and the final error range is +7 bpm. this result is tested in a room with bright and stable light source.

By leveraging these infrared sensor strategies, systems operating in complex space illumination conditions can achieve improved environmental perception and data acquisition, ensuring mission success and system reliability.

We can also combine the infrared with the visible signal from the sensing cameras on robotics to extract the physiological signals with state of art AI technology. Advancements in deep learning technologies have led to the development of numerous new rPPG methods for heart rate measurement, such as 2D convolutional neural network methods, 3D convolutional neural network methods, recurrent neural network method, transformer methods and so on. These methods show excellent results with the visible camera. But there are no good data sets for the infrared cameras combined with visible camera data simultaneously. we will work on building in the future [20].

V. Conclusion and Future work

The integration of artificial intelligence and robotics in extreme environments is pivotal for advancing our ability to tackle complex challenges and perform high-risk tasks. By optimizing the hardware design and leveraging multi-modal sensor redundancy and advanced AI algorithms, we can significantly enhance the reliability, accuracy, and overall performance of systems operating in harsh conditions. We use multi-sensor fusion technology to enhance the reliability of the system. We develop multi-functions of the same sensor to provide redundancy for the system to avoid system failure. We optimize the system both in hardware and software aspects.

Our exploration of key aspects, especially environmental perception, highlights the critical role of sensor data fusion. The combination of infrared and visible light sensors provides a robust and comprehensive understanding of the environment.

Specifically, the proposed non-contact heart rate and temperature monitoring method using RGB visible and infrared cameras demonstrates the potential for improved physiological monitoring in space missions and other extreme environments. The panoramic sensor design with a 270-degree view further enhances environmental perception while reducing mechanical vulnerabilities.

Looking ahead, the rapid development of deep learning technologies presents exciting opportunities for further advancements in remote photoplethysmography methods and other AI-driven applications. By continuing to explore and integrate these emerging technologies, we can achieve even greater levels of precision, reliability, and efficiency in extreme environment operations.

The sensor with wide angle can also be used in applications such as surveillance, fire detection, safety monitoring, physiological signal monitoring, medical endoscopy, field inspection and so on.

In conclusion, the ongoing research and development in AI and robotics hold immense promise for enhancing human capabilities and safety in extreme environments. The insights and design considerations presented in this paper provide a foundation for future innovations, paving the way for more resilient and sophisticated robotic systems capable of thriving in the most challenging conditions.

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Competing Interests

The authors of this paper have no relevant financial or non-financial interests to declare.

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