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Deformation and strength analysis in space structures using optical strain sensors: A review

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Abstract

Real-time monitoring of structural deformation in space infrastructure is a critical factor in ensuring mission reliability and structural integrity. FBG sensors represent an effective solution due to their advantages, such as high sensitivity, low weight, resistance to electromagnetic interference, and multiplexing capability. This review article examines the scientific foundations of using FBG sensors in space environments to accurately monitor structural deformation under conditions including high temperature, radiation, vacuum, and micrometeoroid impacts. Additionally, it analyzes modern research focused on methods of integrating FBG sensors into small spacecraft structures, interrogation techniques, sensor network architectures, and their ability to operate in real time.

Keywords: Fiber Bragg grating, Real-time monitoring, Satellite structural monitoring, Space structures, Structural health monitoring.

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1. Introduction

The long-term reliability and safety of space infrastructure primarily depend on the real-time monitoring of its structural components. This necessity requires sensor systems capable of accurately detecting stress and deformation in space structures. In recent years, FBG technology has gained a prominent position among such systems [1]. The advantages of FBG sensors include resistance to electromagnetic interference, lightweight design, and the ability to operate under vacuum, radiation, and temperature extremes [2]. These features make them significantly more suitable for space applications compared to traditional electrical sensors. Moreover, using spectral interrogation methods, FBG sensors can measure lateral stress in structural elements with high accuracy [1]. Current research thoroughly analyzes the ability of FBG sensors to measure displacement, strain, and stress. These sensors have proven their effectiveness under modern construction and space dynamic load conditions [3]. Additionally, FBG sensor networks embedded in complex structures such as multilayer thermal insulation allow for high-precision, remote, real-time temperature monitoring [4]. Simultaneous detection of temperature and vibration using a single FBG sensor enhances system simplicity and eliminates the need for multisensor configurations [2]. Furthermore, recording deformation and installation accuracy at satellite-rocket interface nodes using distributed FBG sensors increases the assembly reliability of spacecraft [5].

2. Materials and Methods

2.1. Sources of Structural Deformation in the Space Environment

2.1.1. Thermal Limits and Thermal Expansion

Structural elements of space infrastructure must endure thermal cycles involving extreme temperature fluctuations. Understanding these thermal limits and their effects is crucial for monitoring the structural health of composite materials. FBG sensors offer high sensitivity and precise measurement capabilities in this context [6]. Experiments and terrestrial simulations have shown that special configurations of FBG sensors provide high accuracy in measuring complex thermal and mechanical impacts in underground or aboveground structures. These experiments can serve as models for simulating orbital thermal expansion [7].

Different components of composite materials used in spacecraft have varying coefficients of thermal expansion. This characteristic causes micro-deformations and internal stresses between them. Real-time monitoring of such changes is essential for ensuring structural reliability [6]. Furthermore, methods for installing and protecting FBG sensors under long-term thermal and pressure conditions in deep underground structures can be adapted for space applications. These sensors have demonstrated stable performance under high temperature and deep-pressure environments [8]. Monitoring deformations induced by thermal limits using FBG sensors, in combination with traditional structural monitoring systems or visual surveillance and hybrid optical systems, expands the potential of FBG technology. These systems enable detailed analysis of the correlation between structural deformation and temperature [9]. Applied tests have confirmed that FBG sensor arrays can accurately respond to thermal and vibrational changes. Even under conditions of artificial avalanches, where temperature and movement change rapidly, FBG sensors have provided accurate data, which is highly valuable for monitoring abrupt variations in space conditions [7]. The simultaneous measurement of vibration and thermal expansion in rotating shafts of water turbines demonstrates the adaptability of FBG sensors to dynamic thermal loads. Such multifunctional monitoring systems help accurately assess the thermal dynamics of spacecraft [10]. FBG sensors have proven effective in monitoring the thermal cycle resilience of composite structures in reusable missions. Laboratory tests simulating LEO orbit conditions have evaluated the sensors' reliability and durability [6].

FBG sensors' functionality under high-temperature and vacuum conditions enhances the ability to study orbital structures in detail. They can record the condition of thermal insulation devices in real time [11-14]. Moreover, FBG arrays installed on flexible rocket structures can simultaneously monitor thermal and vibrational effects and provide precise data to the control system [15, 16]. FBG sensors are calibrated to respond to a wide range of temperature and deformation variations, maintaining accuracy and stability even under thermal extremes [17]. Compared to other sensor types, FBG technology offers a more effective solution due to its spectral sensitivity and integration capabilities. Under thermal loads, it can register the structural condition with high precision, as shown in Table 1 [18-20]. FBG networks and adaptive filtering methods used for real-time deformation monitoring in wing structures allow accurate modeling of the thermal impact on the structure [21].

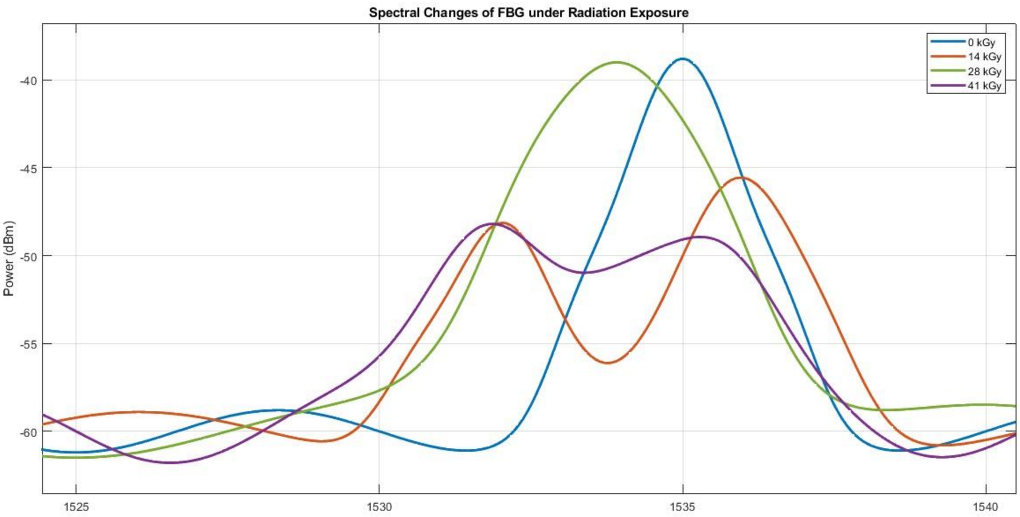
Table 1.
Specific Parameters for Monitoring Thermal Limits and Expansion in Space Structures Using FBG Sensors.

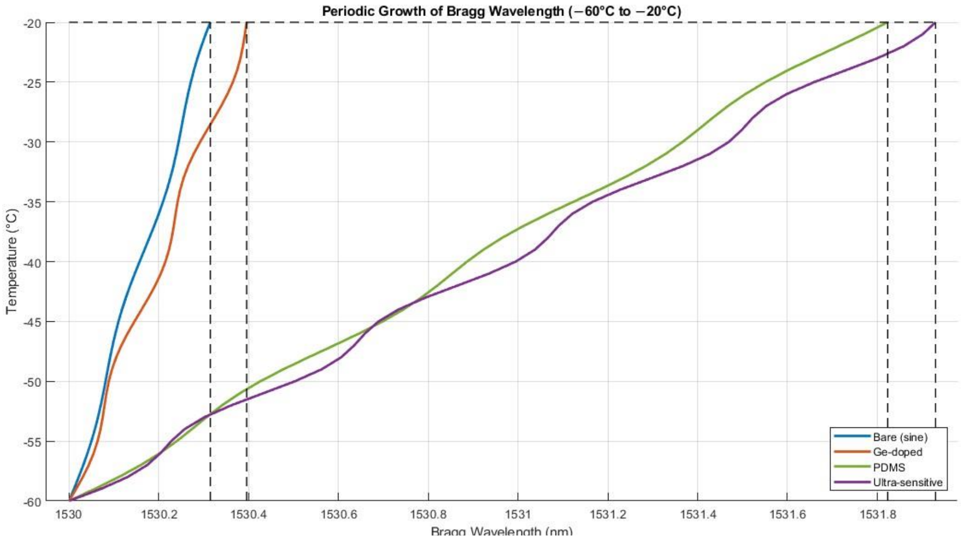
No.	Physical Parameter	Values and Units	References
1	Thermal limits	–150 °C to +150 °C	Tanaka and Yamaguchi [11] and Kim et al. [12]
2	Deformation due to thermal expansion	50–250 με	Liu et al. [10] and Tanaka and Yamaguchi [11]
3	Temperature measurement accuracy of the FBG sensor	±0.1 °C to ±0.5 °C	Zhang et al. [13] and Zhao et al. [14]
4	Temperature fluctuation frequency	2 times per orbital cycle	Tanaka and Yamaguchi [11] and Kim et al. [12]
5	Thermal expansion coefficient of materials	CFRP: 0.5–2.5 μm/m·K	Majumder et al. [6] and Tanaka and Yamaguchi [11]
6	FBG grating placement	High thermal load areas	Majumder et al. [6] and Tanaka and Yamaguchi [11]
7	Thermal displacement	10–500 μm	Wang et al. [7] and Liu et al. [10]
8	FBG sensor response time	0.1–0.3 seconds	Zhang et al. [13] and Li et al. [15]
9	Typical effects of thermal expansion	Internal stress, bending, microcracks	Gao et al. [8] and Tanaka and Yamaguchi [11]
10	FBG grating placement density	Every 1–10 cm	Kim et al. [12] and Li et al. [15]

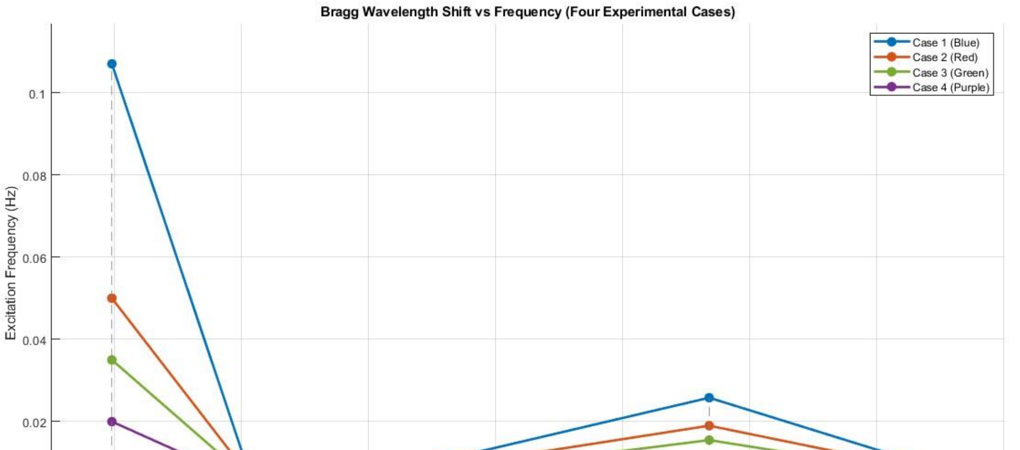
2.1.2. Effects of Radioactive Radiation

In the space environment, structural systems are exposed not only to extreme temperatures but also to intense ionizing radiation, which poses a significant threat to the operational reliability of FBG sensors. Studies aimed at recording impulsive mechanical events have shown that high-energy impacts or radiation-induced vibrations can cause short-lived yet pronounced disturbances in the optical spectrum of a Bragg grating [16]. Embedding FBG sensors within structural elements provides partial protection from mechanical effects; when installed in carbon-composite structures, such sensors can register radiation-induced structural stresses in addition to thermal deformation. This approach has been tested on platforms that simulate real space conditions [22, 23]. FBG sensor degradation in a radiation environment is mainly associated with changes in the fiber's refractive index and absorption coefficients, particularly under gamma rays and neutron fluxes. Radioactive radiation introduces signal distortions such as spectral shifts, increased noise, and reduced sensitivity [24-27]. Experiments have demonstrated that FBG sensors embedded in a carbon platform can monitor not only temperature but also thermo-electric deformations induced by radiation, accurately responding to doses from very low levels up to several hundred kGy [28].

To improve the radiation resistance of FBG sensors, a femtosecond-laser grating inscription technique has been proposed. This method maintains a stable central wavelength and reduces optical losses, allowing the sensors to withstand prolonged irradiation [29]. During long-term missions, cumulative radiation can gradually degrade the optical characteristics of the grating. Studies have shown that long-period gratings and conventional FBG sensors suffer damage to varying degrees, depending directly on their materials and inscription techniques [30]. Detailed investigations of FBG behavior under irradiation reveal time-dependent instability of the spectral response, intensity attenuation, and shifts in the central wavelength after exposure, all of which must be considered to ensure long-term sensitivity and accuracy [31, 32]. To ensure long-term operation in the space radiation environment, researchers are exploring a shift from conventional silica fibers to polymer-based fibers. One example is FBG sensors fabricated from CYTOP polymer fiber, see Figure 1, compiled from four studies, which have shown very high radiation tolerance, remaining effective under gamma-ray doses up to 500 kGy. [33]. These sensors exhibit particularly high reliability under the combined influence of ionizing radiation and temperature. Moreover, FBG sensors are used to monitor both thermal and radiation effects in complex structures. For instance, FBG gratings embedded in phase-change energy-storage structures have been able to record thermo-mechanical deformations precisely and in real time, while also detecting radiation-induced phase transitions within the material [34-36].


Spectral Changes of FBG under Radiation Exposure
Power (dBm)
0 kGy
14 kGy
28 kGy
41 kGy


Periodic Growth of Bragg Wavelength (−60°C to −20°C)
Temperature (°C)
Bare (sine)
Ge-doped
PDMS
Ultra-sensitive


Bragg Wavelength Shift vs Frequency (Four Experimental Cases)
Excitation Frequency (Hz)
Bragg Wavelength Shift (nm)
Case 1 (Blue)
Case 2 (Red)
Case 3 (Green)
Case 4 (Purple)

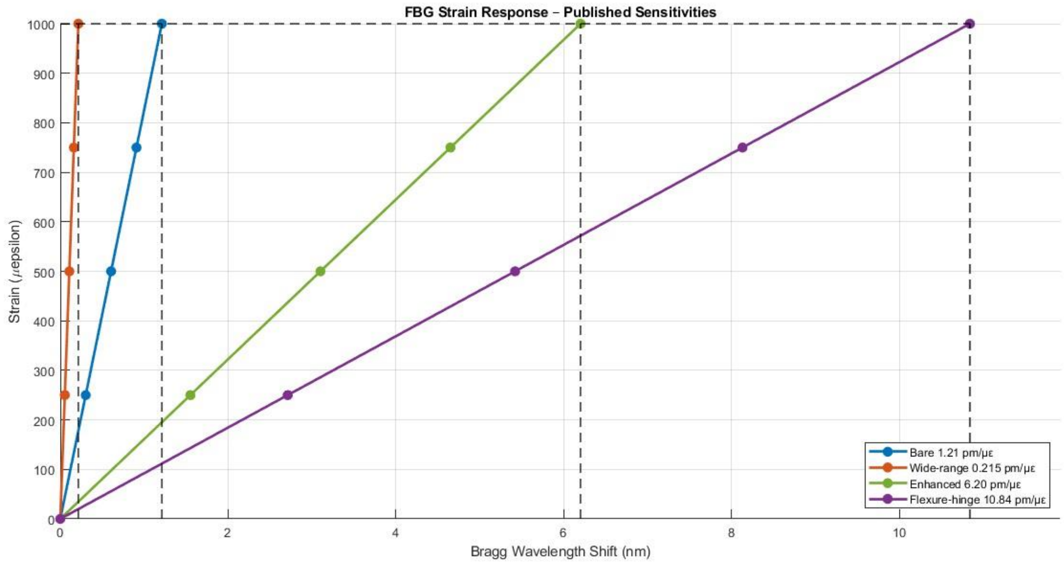


Figure 1.
Spectral variations in a CYTOP fiber: a – Power, b – Temperature, c – Frequency, d – Strain.

2.1.3. Material Behavior in Vacuum Conditions

In space, the vacuum environment imposes unique physical demands on structural materials and their integrated sensor systems, directly affecting the reliability and accuracy of FBG sensor installation. The absence of moisture and the instability of the thermal environment in a vacuum complicate the interaction of hygrothermal and mechanical properties of materials. To precisely measure and distinguish these effects, a new type of sensor based on FBG technology has been developed [37]. Simultaneous measurement of temperature and mechanical deformation in such conditions is crucial. As detailed in Ghaffarian et al. [38] and Liu et al. [39], FBG sensors have demonstrated the ability to accurately record load and temperature under vacuum-like environments. This dual-function monitoring enables comprehensive evaluation of thermo-mechanical responses of materials.

In recent years, FBG sensors have been adapted for use in vacuum and harsh conditions, showing significant improvements in fast response, high spectral stability, and long-term calibration reliability [40]. These advantages form the foundation for the accurate recording of material states in a vacuum. Furthermore, Sun et al. [41], Huang et al. [42], and Jin et al. [43] found that the resistance of sensor gratings to hygroscopic effects helps ensure high-precision measurements in vacuum conditions. These sensors enable accurate modeling of environmental influences, particularly in monitoring internal temperature and humidity fluctuations.

The issue of writing FBG gratings on hydrogen-loaded optical fibers and enhancing their thermal stability in vacuum was addressed in Liu et al. [44]. In this study, gratings were inscribed using a 266 nm laser, showing improved thermal stability, which enhances sensor reliability in long-term space missions. Methods for improving deformation compensation in temperature-sensitive FBG sensors for vacuum applications were proposed in Dias et al. [45]. This research outlined techniques for eliminating deformation during integration into ionic environments, enabling more accurate temperature responses from the sensors.

FBG sensors can also be paired with advanced optical signal processing technologies to efficiently analyze temperature, pressure, and strain parameters under extreme conditions, including vacuum [46]. Furthermore, Lin et al. [25] presented specific examples of how changes in the thermo-optic coefficient of materials in vacuum influence sensor spectra. In such conditions, the wavelength shift of the FBG grating can be a valuable diagnostic tool in sensor system control. Lastly, radiation in a vacuum can also affect the internal structure of materials and the stability of gratings. These changes may cause wavelength shifts, requiring recalibration of the sensors' accuracy [47, 48]. Table 2 presents concrete indicators of FBG technology's high precision, electromagnetic stability, and suitability for multipoint monitoring.

Table 2.
Comparative Table of Methods for Detecting Deformation in Space Infrastructure Using FBG Technology.

Detection Method	Operating Principle	Advantages	Disadvantages
FBG-Based Deformation Monitoring	Detects shifts in the wavelength of reflected light via a Bragg grating inscribed in an optical fiber	– High accuracy – Resistant to electromagnetic interference – Compact and lightweight – Enables multipoint monitoring with a single fiber	– High cost – Complex installation (requires precise calibration) – Needs spectral analysis equipment
Thermocouples and Traditional Sensors	Converts changes in temperature or strain directly into an electrical signal	– Low cost – Easy to install – Familiar to engineers	– Sensitive to electromagnetic fields – Less reliable in space vacuum and radiation – Measures only at a single point
Interferometric Optical Methods	Measures deformation through light interference phenomena	– High sensitivity – Detects microscopic changes	– Complex setup and configuration – Susceptible to vibration and temperature instability
Vision-Based Monitoring	Registers visual changes using cameras and image processing algorithms	– Visual confirmation – Suitable for remote monitoring – Operates without additional sensors	– Dependent on lighting and visibility conditions – Cannot observe internal structural deformations

2.1.4. Mechanical Vibrations and Micrometeoroid Impacts

During flight, spacecraft are subjected to various external and internal mechanical influences, including high-frequency vibrations and micrometeoroid impacts. These effects pose risks to structural stability and can negatively affect long-term performance. To accurately and reliably detect such factors, FBG sensors are being utilized. FBG sensors have demonstrated high sensitivity in monitoring the vibration modes of carbon composite antenna booms. They accurately record vibration signals in the 25–1500 Hz frequency range, enabling precise characterization of the dynamic behavior of structural elements [30].

In addition, internal turbulent flows generated by thermohydraulic processes sometimes result in localized micro-vibrations within the structure, which can also be successfully monitored using FBG sensors. The technology can distinguish such signals and accurately determine the origin of the vibration. The operating principle is illustrated in Figure 2 [6, 49, 50].

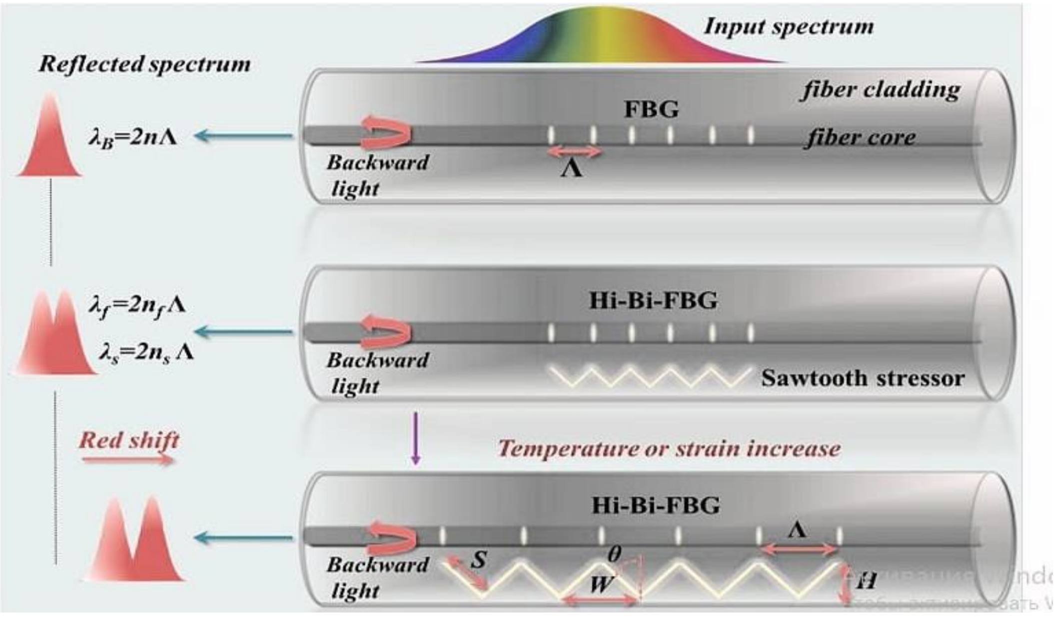


Figure 2.
Schematic Diagram of the Operating Principle of an FBG Sensor.

At high temperatures, the shift in the Bragg wavelength of the sensor grating can be monitored with extremely high precision at the level of ±1 picometer. This capability is especially important for accurately detecting thermal and structural deformations following micrometeoroid impacts [51]. FBG sensors also enable long-term monitoring of instabilities in thermohydraulic conditions, providing a comprehensive understanding of the structural response. This establishes them as reliable diagnostic tools under complex conditions [52-54]. Table 3 systematically describes the specific role of FBG sensors in detecting mechanical hazards in space infrastructure.

Bragg gratings with high birefringence, inscribed using femtosecond lasers, can clearly distinguish between temperature and strain signals. These sensors are especially useful in structural components exposed to complex influences, as their output data appear spectrally distinct [55]. By integrating FBG sensors into structural control systems, it becomes possible to continuously monitor displacement, vibration, and the effects of micro-impacts at precise locations. Such monitoring systems play a critical role in ensuring the long-term stability of spacecraft [56].

Table 3.
FBG Sensors for Detecting Vibration and Impact in Space Structures.

Research Area	Application Context	Key Advantage
Vibration Monitoring in Antenna Structures	Monitoring high-frequency vibrations	Precise spectral characterization
Vibration from Turbulent Flow Effects	Detection of internal microseismic oscillations	Additional thermohydraulic monitoring
Wavelength Shift Due to Temperature	Detection of thermal changes after micro-impacts	Picometer-level precision
Separate Measurement of Temperature and Strain	Sensor reliability under complex loading conditions	Ability to decouple parameters
Monitoring Integrated with Active Structural System	Real-time assessment of structural response	Fast response and adaptability to control

3. FBG Sensor Operating Principle and Scientific Basis

3.1. Optical Properties of Bragg Gratings

The operation of FBG sensors is based on the optical properties of Bragg gratings. These gratings are regions within the optical fiber where the refractive index varies periodically. They reflect light at a specific wavelength while allowing all other wavelengths to pass through. This characteristic enables precise detection of strain and temperature variations. In the optical signal retrieved from the sensor, accurately identifying the Bragg reflection peak is essential. To achieve this, peak tracking methods are employed. Stable and precise tracking of the Bragg peak in the light spectrum enhances the sensitivity and accuracy of the sensor [11, 57, 58].

To reduce system costs, simple and low-cost interrogators for FBG sensors are being developed. These devices allow for dynamic strain detection and are suitable for real-time analysis [36]. For example, to improve the effectiveness of peak tracking methods, signal interpolation and filtering algorithms are implemented. These approaches enable sub-nanometer precision in identifying peak shifts. They also enhance reliability in noisy environments. The main types of such methods are shown in Table 4 [59].

Table 4.
Main Peak Tracking Methods for FBG Sensors.

Method Type	Common Techniques Used
Direct	Maximum value detection, Centroid method
Curve Fitting	Second-order polynomial approximation, Gaussian fitting
Correlation-Based	Cross-correlation, Correlation followed by polynomial fitting
Resampling	Increasing sampling frequency, Resampling
Transform-Based	Fast phase correlation, Wavelet transform
Optimization-Based	Neural networks, Genetic layered discrimination

Since FBG sensors are highly sensitive to both temperature and mechanical strain, they are widely used in structural health monitoring systems. A schematic diagram illustrating their operating principle is shown in Figure 3. These sensors enable multipoint measurements, allowing precise detection of localized deformations within structures [60]. FBG sensors can accurately record not only static but also dynamic deformations. Research findings have demonstrated how the sensors capture time-dependent variations under load, particularly in complex structures such as windings or shells [5].

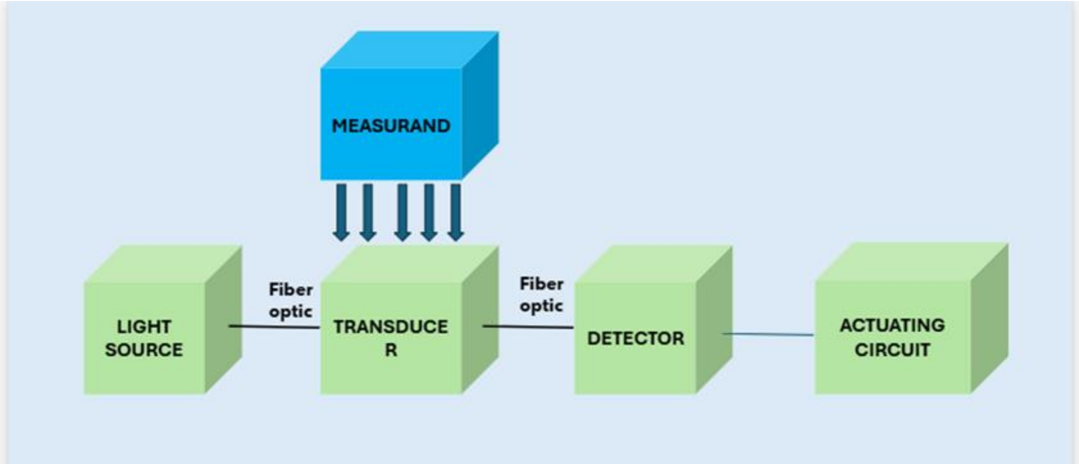


Figure 3.
Schematic Diagram of the Operating Principle of an FBG Sensor.

Artificial intelligence methods are increasingly being introduced to calibrate FBG sensors and refine their response functions. For example, the OSELM algorithm enables fast processing of the sensor's dynamic characteristics and delivers accurate results [61]. Writing Bragg gratings into CYTOP fibers, which have a lower refractive index than quartz, increases their sensitivity to temperature and humidity. CYTOP-based sensors have demonstrated high stability in radiation-rich environments, making them suitable for space applications [62].

Another study evaluating the response of FBG sensors to dynamic loads in structural elements showed that the sensors could accurately detect real-time strain distribution, enabling early identification of structural changes [63]. FBG technology is widely used not only in industrial settings but also in safety systems. For instance, their application in monitoring wall movement in mines to prevent accidents illustrates the effectiveness of such sensors in structural monitoring. This approach can also be successfully adapted to space infrastructure [64].

3.2. Wavelength Shift Due to Strain and Temperature Effects

FBG sensors detect structural changes caused by external temperature and mechanical strain through shifts in wavelength. This method is based on the optical grating parameters of the sensor. The reflected wavelength in a Bragg grating directly changes depending on the mechanical and thermal state of the material. In complex and dynamic processes within space infrastructure, this property enables an accurate assessment of structural condition. Chirped-type FBG sensors, due to varying grating periods along a single grating, allow simultaneous data collection from multiple zones. This enhances their effectiveness as multiparameter measurement tools. Specifically, during temperature changes, spectral broadening enables precise localization of deformation. Studies have shown that such sensors maintain spectral stability even during long-term use, making them highly effective for orbital monitoring [65].

Modeling distributed sensing systems in aerospace structures can benefit from formal logic-based frameworks developed in other domains. The station is a collection of automata interacting with each other in discrete time, where operational procedures are described using state machines and connected acyclic graphs. This hierarchical modeling strategy offers a transferable framework for structuring the logic and data flow within FBG sensor networks, allowing more efficient signal interrogation, event tracking, and system coordination [66].

The method of installing FBG sensors on a structural surface significantly affects measurement accuracy. UV-curable resin layers improve adhesion between the sensor and the structure, ensuring stress is transmitted to the sensor without loss. Using this approach, sensors can be placed on flexible, complex geometries or layered composite surfaces with minimal signal degradation. Additionally, the resin protects the sensor from environmental influences, supporting its long-term operation. These coated sensors have proven to function with high precision on aircraft fuselages, wind turbine structures, and space mechanical joints [67]. FBG sensors embedded within capillaries inside rigid structures can directly capture internal temperature and strain. This technique enables simultaneous data acquisition at multiple internal points. Internal embedding protects sensors from mechanical damage, UV exposure, and abrupt external temperature changes. This method allows long-term monitoring of building supports, satellite components, or fuel tanks. Furthermore, improved sensor accuracy and stability within the structure minimize signal loss and enable the creation of an accurate deformation map. This is especially effective for assessing the distribution of thermal deformation along the structure [41].

This principle of adaptive embedding corresponds to structural solutions found in land-based transport mechanisms. For example, a chassis with parallelogram suspension architecture that maintains vertical body orientation regardless of gradient variation. This geometry enhances deformation stability and can be extrapolated to the design of flexible satellite panels [68].

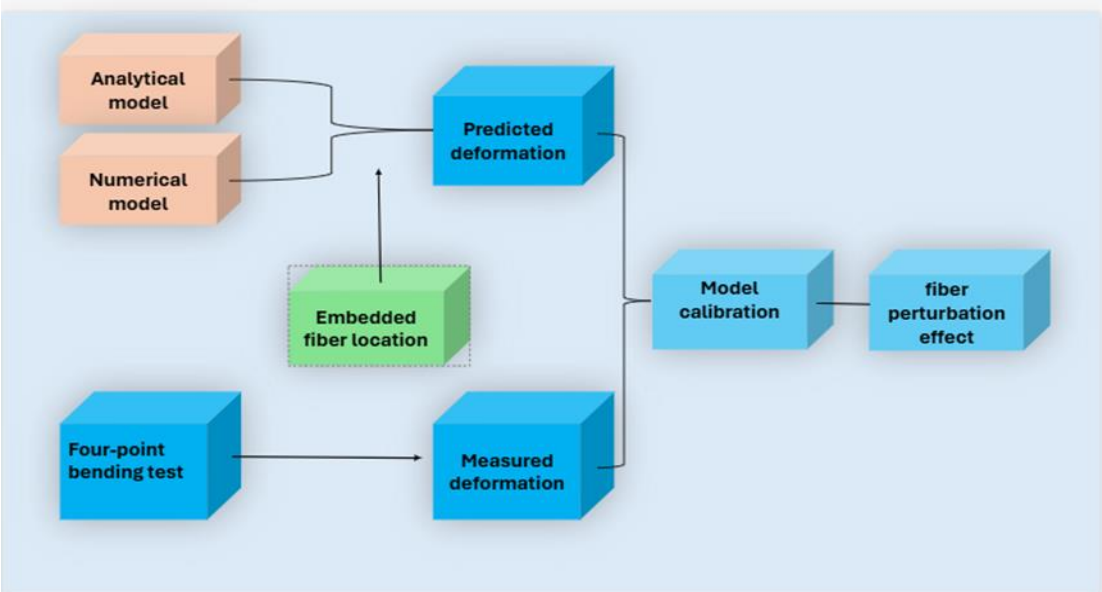


Figure 4.
General View of the Methodological Approach.

Analysis of deformation changes is crucial not only for assessing structural reliability but also for determining flight readiness. Data obtained from Bragg gratings can be used to detect early-stage faults such as fatigue, cracks, and stress concentration within a structure. In aerospace vehicles, such analysis helps reduce the frequency of maintenance and prevent major repairs. Moreover, integrating data analysis with automated systems enables the adaptation of sensor networks for large-scale space missions. This is vital for continuous structural health monitoring and ensuring compliance with technical safety standards [1, 18].

The Distributed Fiber Optic Sensor method allows spatial visualization of changes caused by temperature and strain as a precise map. These sensors can extend over several meters along a structure, providing accurate measurements at multiple points. As clearly shown in Figure 4, the correlation between strain and temperature is reflected at various wavelengths in the Bragg spectrum. Studies have demonstrated that this method enables simultaneous monitoring of several structural zones and precisely identifies localized stress concentrations and thermal transitions. Additionally, DFOS technology has proven effective for detecting internal cracks in complex materials, such as carbon composites [4, 69].

The use of unmanned aerial vehicles is expanding the capability to collect real-time deformation and temperature data. When integrated with FBG sensors, such platforms enable mobile structural monitoring during emergencies or critical situations. Research has shown that these sensor systems are effective for remotely assessing the condition of buildings or satellite structures during extreme events. Furthermore, mobile platforms can collect data rapidly and efficiently, allowing for accurate decision-making based on Bragg wavelength shifts. This is particularly important during natural disasters, pre-launch spacecraft inspections, and in-orbit servicing operations [70].

3.3. Static and Dynamic Modes

Structural components in space infrastructure are simultaneously subjected to both long-term static and short-term high-frequency dynamic loads. In these cases, FBG sensors provide reliable and accurate detection of micro-level deformations. In static modes, FBG sensors are widely used to monitor slow, gradual stress and thermal expansion processes in spacecraft structures. For example, in systems designed to identify space debris materials, FBG sensors recorded minor deviations under static conditions, proving effective in classifying material types. This classification method provides a foundational reference to compare with later dynamic changes [71]. In addition, static sensor data has been used in AI-based automated systems to train models and determine optimal control strategies. These steady-state readings also help define subsystem reliability limits [72]. FBG sensors embedded in composite materials can detect micro-level loading. Studies have shown that these sensors enable the mapping of stress-temperature relationships inside structures, allowing the prediction of damage-prone areas and forming the basis for predictive maintenance [73]. In aircraft landing gear structures, Bragg gratings have captured real-time strain and geometric displacements, allowing precise assessment of how static loads contribute to deformation, ultimately informing evaluations of long-term structural durability [49]. In exoskeleton robotics, sensors that detect muscle-joint positions in static posture have helped model a person's readiness for movement, linking the initial balance state to motion onset [74]. Further studies analyzing thermal-strain records in static conditions in composite structures confirmed the long-term reliability of the gratings [14].

In dynamic modes, FBG sensors accurately measure high-frequency, short-duration vibrations and impacts in real time. For example, in multi-camera visual SLAM systems, these sensors have been used to monitor the position, velocity, and orientation of moving space platforms. Their data, synchronized with visual tracking systems, enabled precise control of integrated system responses [11]. Bragg gratings embedded in CFRP and other composites allow sensors to measure impact force, direction, and propagation time. Combined with machine learning algorithms, this enables accurate localization and characterization of damage [75]. In exoskeleton systems, FBG sensors monitor joint angle variations during dynamic movement, providing full-body motion tracking and enabling integration with biomechanical control systems [76]. A schematic representation of how FBG sensors identify deformations in space infrastructure is presented in Figures 5 [6, 52].

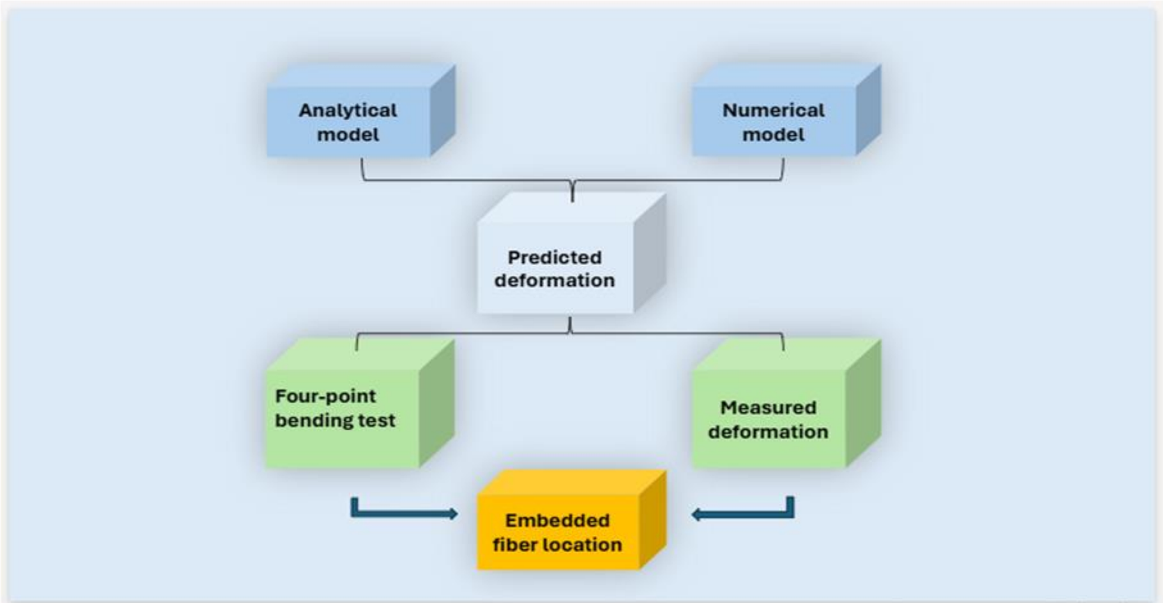


Figure 5.
Monitoring Process of Structural Loads in Static and Dynamic Modes Using FBG Sensors.

FBG sensors have also demonstrated high sensitivity in detecting the effects of vibration and torque-induced stress in rotating structures. This capability is particularly important for space-based power transmission systems, thermal rotors, and solar panel steering mechanisms [77]. Furthermore, pre-trained neural network models are increasingly being employed to associate sensor outputs with complex systems such as image interpretation. This integration allows for the visualization of complex dynamic processes in an interpretable and intuitive format [4].

Table 5.
Monitoring of Static and Dynamic Deformation in Space Infrastructure Using FBG Sensors.

No.	Application Area	Role of FBG Sensor	Key Scientific Finding	Reference
1	Space debris material	Recording static impact	Accurate material classification was achieved based on FBG sensor data	Nguyen et al. [47]
2	Space structure (composite)	Monitoring stress and deformation	Damage indicators were detected early, enabling real-time structural health monitoring	Majumder et al. [6]
3	Aircraft landing gear system	Measuring load and temperature	Stress and thermal effects were quantified, and long-term structural reliability was assessed	Zhang et al. [49]
4	CFRP materials	Detecting dynamic impacts	Impact location and intensity were quickly and accurately identified using ML and FBG data	Lin et al. [52]

4. Applications of FBG Technology in Space

4.1. Precise Deployment Methods for Space Structures

To accurately measure structural deformation in space infrastructure, the efficient integration of FBG sensors into the structure is one of the primary requirements of the sensing system. By optimizing the physical position of the sensor, its mounting angle, and the type of contact with the surface, the signal quality and long-term stability can be significantly improved. This approach allows for accurate detection of thermal, vibrational, and mechanical variations in spacecraft. During sensor installation, the material properties of the structure must be considered to minimize their impact on the optical reflection behavior of the sensor. Such precise deployment solutions can also be linked with video processing technologies. For example, using video stitching techniques, structural parts where sensors are located can be digitally merged to spatially map their deformation. This method enables geometric correction of sensor regions using a local homography matrix, allowing for digital visualization of deformation dynamics. Integrating FBG data onto actual structural surfaces enables correlation of deformation patterns with 3D models [78].

The optimal spatial arrangement of sensors depends on the network architecture and sensor topology. Algorithms such as Delaunay triangulation and simulated annealing can be used to calculate the most efficient sensor distribution. These techniques take into account the distance between sensors, signal quality, and structural interaction. As a result, a sensor network is formed that ensures full data coverage and reliable transmission [79]. Similar multi-criteria optimization principles are also applied in other domains. The tasks of organizing tourist transportation and designing tour routes are tasks of multi-criteria optimization [80]. During deformation, space structures experience complex shape changes, which require visual interpretation of sensor signals. The Vision Transformer architecture offers an effective solution in this context. This method uses machine learning to model motion and deformation patterns based on visual processing of signals from FBG sensors. Additionally, it automatically classifies incoming data streams and facilitates early detection of structural changes [81].

A study conducted on reusable composite panels proposed embedding FBG sensors into internal capillaries. This capillary integration method isolates the sensors from external influences, enhancing their longevity and sensitivity. Isolating the sensors from the environment also reduces signal drift and allows for accurate measurement of real structural stress and temperature. Furthermore, panels embedded with sensors were tested under LEO (Low Earth Orbit) conditions for extended periods and demonstrated high operational efficiency [82].

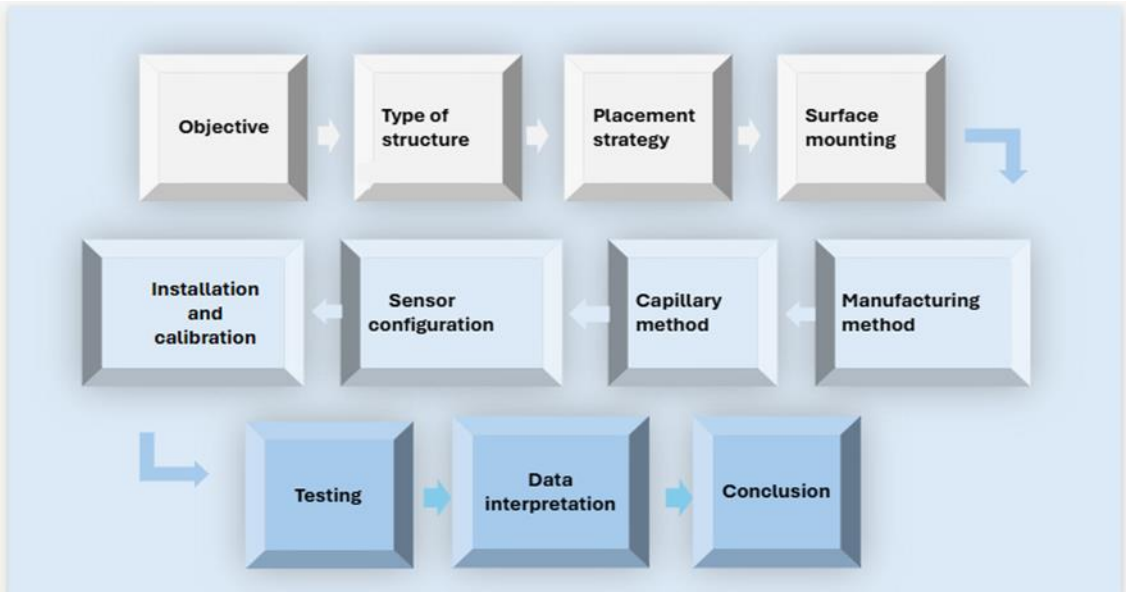


Figure 6.
Step-by-step block diagram of FBG sensor deployment in space structures.

Sensors can also be used to detect impact effects. For instance, by embedding FBG gratings inside a composite tube, it became possible to detect low-velocity impacts in real-time. The sensors accurately measured micrometeoroid impacts, structural fatigue, or mechanical contact from external objects and transmitted the data via telemetry systems. This method is particularly useful for identifying passive effects in orbit. Additionally, the general layout of FBG sensor placement in space structures is shown in Figure 6, which can be considered a logical diagram of a structural health monitoring system based on FBG sensors [83].

Upon revisiting this method, it was found that embedding the sensors into internal capillaries significantly enhanced their resistance to thermal and mechanical drift. Distinguishing between thermal effects and mechanical strain in the sensor signals became easier, improving the overall reliability and calibration of the sensor system. The response time to thermal expansion and vibrations in the structure was also reduced [84-86]. In this context, the integration of finite element modeling platforms such as MSC Marc and Mentat can support the simulation of thermal loads, structural deformation, and contact interactions, providing a validated framework for optimizing FBG sensor deployment in space environments [87]. Similarly, when placing FBG sensors on wing-like structures, the iFEM (inverse Finite Element Method) was widely applied. This technique automatically determines the most effective sensor placement points by reverse-calculating the structure's shape. During modeling, the number of sensors, their orientation, and thermal compatibility were considered, providing a solution that ensures complete structural shape monitoring. Such models are highly beneficial for complex constructions in spacecraft, satellites, and robotic platforms [88].

This modeling logic aligns with the concept of decentralized control systems used in industrial applications. The control system combines classical decomposition with situational decomposition, improving efficiency and reliability in complex technological processes. The Trace Mode software platform supports multi-tiered, situationally adaptive control architectures, which can be conceptually applied to the design and coordination of fiber optic sensing systems for structural health monitoring in space infrastructure [89].

4.2. Orbital Platforms and Laboratory Demonstrations

The combination of FBG and CFBG-FP sensors based on optical fibers has enabled the development of a new generation of fully optical sensors for determining the orientation of spacecraft. This sensor system was used to measure pitch, roll, and yaw angles during flight, achieving an accuracy of 1.5° for pitch and roll within a 180° range, and 1.3° accuracy for yaw detection. The study demonstrated that this sensor architecture is reliable and thermally stable for use in space navigation applications.

To monitor the state of the interface between a rocket and a satellite, a distributed fiber-optic sensing system was proposed. Strain values at the connection point were precisely monitored both during and after installation. This study utilized a specialized OFDR (Optical Frequency Domain Reflectometry) technology, which enabled accurate mapping of structural conditions and optimization of installation precision. This approach allowed for the early prediction and control of microscopic strain developments within the structure [90].

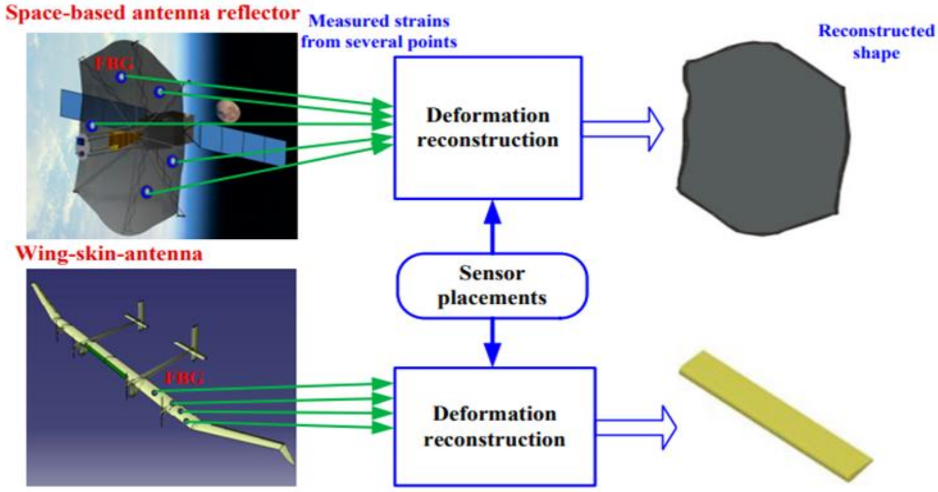


Figure 7.
Schematic diagram for detecting shape deformation based on FBG strain sensors.

4.3. Orbital Platforms and Laboratory Demonstrations

A total of 780 FBG sensors were installed on a composite wing panel of a commercial aerospace structure to precisely measure actual flight loads and deformation shapes. The sensors enabled the reconstruction of the wing's exact shape with an error margin of 4.2%. The study demonstrated that mechanical vibrations and aero-pressure effects propagating over time could be effectively monitored through the sensors, validating the method's efficiency for large-scale structures [91].

To address the challenge of optimally placing FBG sensors on complex-shaped structures such as antennas, a placement optimization algorithm was proposed. Based on modeling, this method identifies regions experiencing maximum strain in advance, allowing for maximum data acquisition with a minimal number of sensors. This approach helps reduce the weight of the sensor network while maintaining signal quality [62]. A demodulation system based on FBG sensors that does not require temperature compensation was developed under laboratory conditions. Built on a PWM foundation, the system enables accurate, temperature-independent detection of multi-point deformation and vibration. It is designed for multisensor networks and adapted for real-time structural diagnostics [92].

Returning to the antenna structure, the study demonstrated how sensor placement, mechanical integration methods, and correlation with computed strain fields contributed to a minimally invasive yet highly accurate sensor network. This system was proven to be suitable for evaluating spacecraft safety both pre-launch and during flight, and its schematic is shown in Figure 7 [93]. in experimental studies aimed at monitoring the condition of solid-fuel rocket engines, FBG-based sensors effectively captured mechanical stress and temperature, even during explosive events. These sensors were shown to survive and function under such extreme conditions [94].

In multilayer composite structures, the method of embedding sensors directly during the manufacturing process enabled accurate tracking of internal loads, cracks, and vibrations. The sensors were evenly distributed across the panel, detecting internal stress and resonant vibrations with high accuracy. The study also highlighted the mechanical robustness of sensor cables and optical connectors [95]. In laboratory experiments on pipe-like composite structures, FBG sensors accurately recorded vibration and impact loads, allowing for a quantitative assessment of micro-deformations within the structure. Sensor responses under different loading scenarios were compared, and their sensitivity and repeatability characteristics were analyzed [86].

In a follow-up study, the performance of sensors and optical modules embedded directly into composites during manufacturing was evaluated with high precision. Multi-point measurement was implemented in panel structures, and the sensor network demonstrated strong reliability, protection, and data transmission capabilities [96].

4.4. In-Mission Results and Reliability Indicators

A new method proposed for identifying damage locations in spacecraft's segmented structures reconstructs the stress field based on strain measurements from FBG sensors. This method calculates stress difference norms and maps deformations with precise coordinates. Its key advantage lies in enabling accurate identification of deformation sources even on complex surfaces using automated processing algorithms, thereby supporting informed decision-making regarding the structural state. The system plays a crucial role in maintaining spacecraft functionality and ensuring mission safety [97]. High radiation environments can interfere with the stable operation of FBG sensors. However, studies show that with certain configurations and protective techniques, sensors can operate correctly over long durations. Spectral shifts in the grating period under gamma irradiation affect sensitivity, but with proper materials and filtering techniques, this effect can be mitigated. The study also considers long-term calibration requirements, proving that sensor systems can be adapted effectively for use in real space conditions [98].

A spectral separation method using FBG gratings was developed to monitor lateral stress in spacecraft. This system captures spectral shifts in the reflected light from FBGs to provide a detailed profile of transverse stresses. Its unique advantage lies in being temperature-independent. Tests on orbital platforms confirmed the sensors maintained reliable readings even under multiple thermal cycles, proving their high sensitivity to both strain and stress direction [99]. By visualizing the stress field as a map based on FBG data, it becomes possible to evaluate damage-prone areas in advance. While earlier studies validated this method through simulations, current mission data confirm its practical value. The sensor system plays a key role in predictive maintenance and structural health monitoring before scheduled servicing. Its main benefit is the ability to diagnose accurately by processing deformation data automatically [83].

FBG sensors installed on reusable composite space structures successfully passed multiple tests. Despite exposure to temperature, radiation, and mechanical loads, the sensors accurately measured internal stresses and thermal expansion. Studies reported several months of continuous monitoring on solar arrays, thermal panels, and composite walls, with real-time precision data contributing significantly to mission safety [100]. In multilayer insulation coatings, FBG sensor networks captured thermal dynamics and deformation data, enabling precise control of spacecraft thermal regulation systems. These sensors provided real-time feedback on temperature fluctuations, micrometeoroid impacts, and internal structural stresses. Adapted to architectural design, the network allowed early detection of thermal anomalies [101]. Radiation is known to affect the spectral characteristics of FBGs. High-dose exposure alters the grating period, causing spectral shifts and reducing sensitivity. This study demonstrated that careful selection of sensor materials, protective capillary coatings, and pre-calibration can significantly enhance radiation tolerance. These improvements make FBGs increasingly viable as long-term, reliable tools for space structural monitoring [102].

A detailed methodology for deploying FBG sensors in reusable space-grade composite structures is described. It includes efficient in-structure placement, use of radiation- and temperature-resistant materials, and real-time integration of data into structural health monitoring systems. These practices are crucial for ensuring the durability and reliability of sensor networks [103]. Figure 8, presented in the paper, illustrates the process of installing and testing FBG-based sensing systems in multilayer thermal insulation coatings is illustrated. The block diagram systematically outlines all major steps from sensor integration to calibration, thermal testing, and data acquisition.

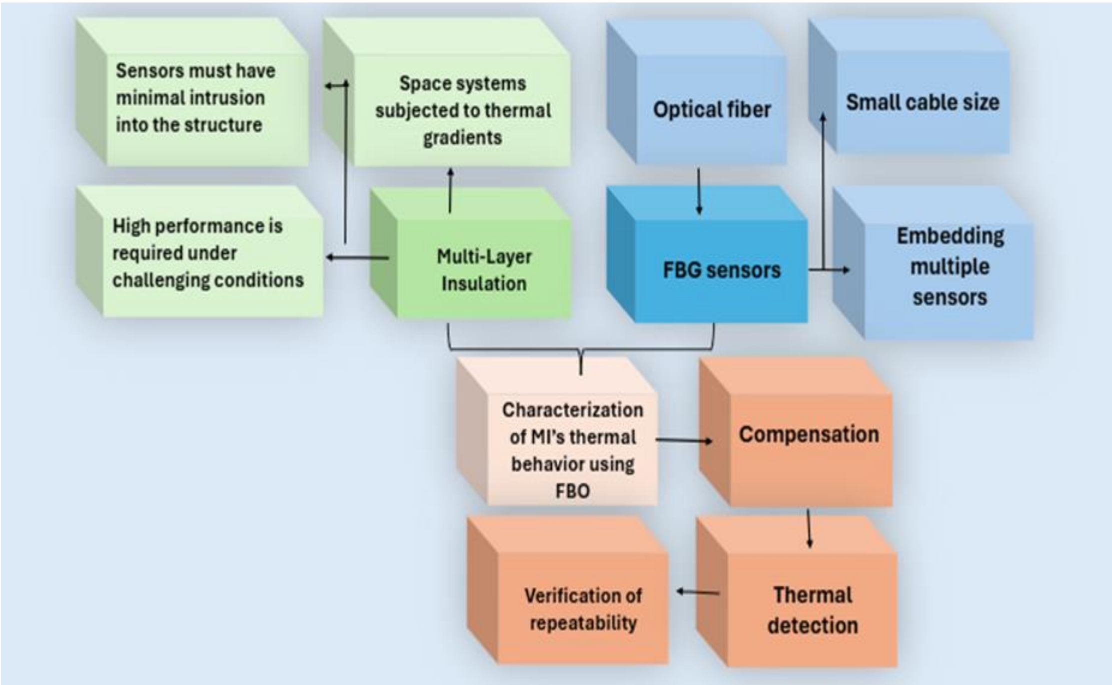


Figure 8.
Block Diagram of the Main Operational Stages Described in the Study.

Table 6.
Key results and reliability indicators obtained during the mission.

No.	Key Result	Reliability Indicator
1	Accurate localization of damage through reconstruction of the deformation field	Operates with high precision in complex structures
2	Maintaining sensor stability in high-radiation environments	Long-term reliability ensured through spectral shift adjustment
3	High-accuracy identification of lateral stress using the spectral separation method	Verified in actual orbital tests, high sensitivity
4	Long-term monitoring of reusable composite structures	Stable and reliable operation under temperature and radiation conditions
5	Real-time monitoring of temperature and stress in thermal insulation coatings	Continuous monitoring capability, highly stable sensor network
6	Detection of spectral shifts and structural disturbances in sensing gratings due to gamma radiation	Radiation-resistant methods proposed, suitable for harsh environments

5. Relevance of Using FBG Sensors for Structural Deformation Monitoring in the Space Environment

5.1. The Necessity of Real-Time Structural Health Monitoring Under Space Environmental Factors

The operational conditions of space structures, such as extreme temperature gradients, radiation, vacuum, micrometeoroid impacts, and vibrations, impose unique demands on sensing systems. In such a harsh environment, accurately and reliably monitoring the structural state in real time is essential to ensure the safety and long-term functionality of space infrastructure. This need becomes more pronounced with the advancement of autonomous systems. One promising solution to address these challenges is the use of optical fiber-based structural health monitoring systems. Recent studies have shown that integrating this technology with artificial intelligence enables real-time processing of sensor data and early detection of structural anomalies.

For the implementation of real-time expert analysis and deformation prediction in complex infrastructure systems, the approach based on the modified Delphi method (MDM) can be adapted to enhance structural health monitoring (SHM) in space environments using FBG sensor data [66].

Fiber-optic sensors have demonstrated their reliability and resilience in space applications. They can be easily embedded into complex structures and are capable of simultaneously monitoring multiple parameters such as strain, temperature, and pressure. Key advantages of these systems include immunity to electromagnetic interference and long operational lifespan. FBG technology's ability to operate in extreme environments is one of its most notable advantages. Femtosecond laser-inscribed gratings provide high radiation and temperature stability, allowing for long-term precise measurements. These gratings have exhibited high sensitivity even under the boundary conditions of space environments [73]. Although FBG sensing technologies were initially developed for monitoring historical structures, their multifunctionality and high precision have made them adaptable to modern space infrastructure. For instance, during the monitoring of ancient wooden structures in China, the sensors demonstrated high sensitivity to both dynamic loads and thermal changes [104].

As the design and application scope of sensors have expanded, FBG technology has consistently demonstrated superior performance in terms of accuracy and long-term stability when compared with other measurement techniques. Moreover, the installation of this technology is relatively simple and flexible. Real-time monitoring of reusable composite structures in orbit is another compelling example demonstrating the effectiveness of these sensing systems. The sensors provided continuous and accurate data on strain and thermal changes during prolonged orbital loading, offering crucial insights into structural reliability.

Table 7.
Advantages of Real-Time Structural Monitoring in the Space Environment.

No.	Advantage	Description
1	Rapid response to temperature changes	Enables real-time monitoring of thermal deformation in the structure.
2	Detection of radiation effects	FBG sensors identify structural changes caused by radiation at early stages.
3	Resistance to mechanical vibration and shock	Responds to vibrations during rocket ignition and micrometeoroid impacts.
4	Early warning and prevention	Enhances the ability to prevent emergencies through early fault detection.
5	Comprehensive monitoring via sensor networks	FBG sensors collect data from multiple points, allowing full monitoring of the entire structure.

5.2. Advantages and Application Potential of FBG Sensors in Harsh Environments

Real-time, accurate, and reliable monitoring of structural deformation under harsh conditions is a critical requirement for the safe operation of modern space, marine, geotechnical, and civil infrastructure. Fiber Bragg Grating (FBG) sensors stand out as a unique technology in addressing this challenge. Their high sensitivity, compact size, resistance to electromagnetic interference, and multi-point measurement capability offer significant advantages for operation in complex and aggressive environments. The ability of FBG sensors to function under extreme conditions has been demonstrated in studies involving hard-landing scenarios. Deformation levels during landings on different soil types were accurately recorded, confirming the mechanical resilience of the sensing system [77]. Additionally, when integrated with ultrasonic inspection, FBG sensors enable early detection of internal structural defects. This technology is used for diagnosing structural health under conditions of intense vibration or impact [105].

In marine infrastructure, FBG sensors are increasingly used. Under fluctuating pressure, humidity, and temperature, optical sensors have demonstrated more reliable long-term monitoring results compared to traditional methods [77]. In space infrastructure, networks of FBG sensors enable real-time monitoring of MLI thermal insulation layers. This technology provides accurate detection of heat flow variations over time, helping maintain thermal equilibrium and ensuring structural functionality [14]. FBG sensors have also proven effective in ground-based and geotechnical applications. For instance, systems used to monitor deformation in traditional wooden structures have demonstrated the capability of these sensors to monitor structural changes over long periods [78]. Monitoring systems in geotechnical centrifuge testing have successfully recorded complex phenomena such as soil movement and landslides [79].

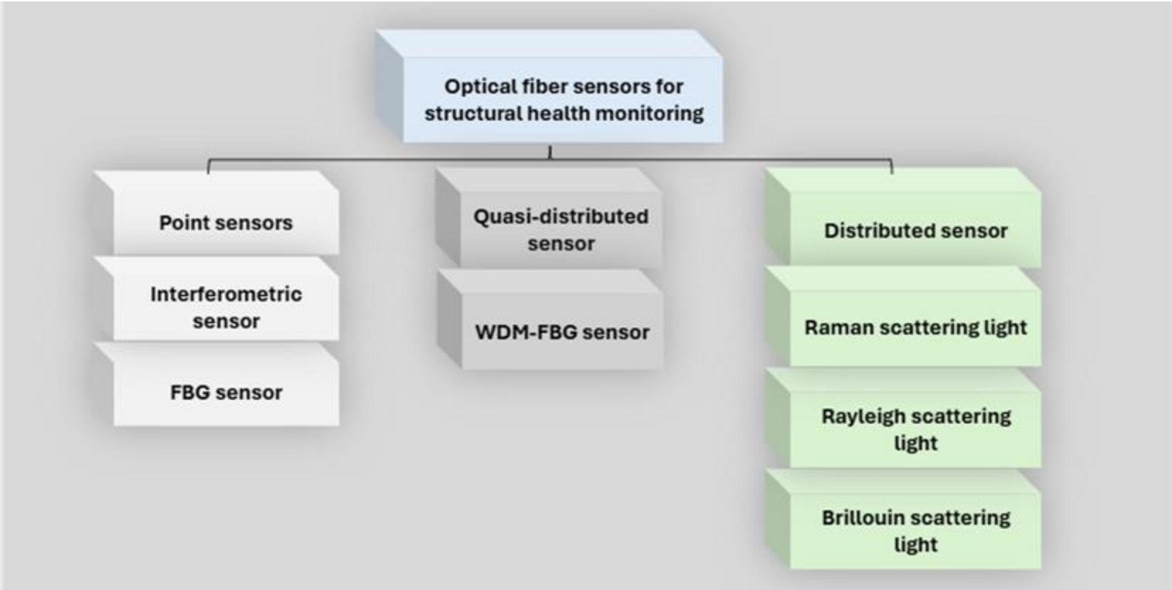


Figure 9.
Overview of Fiber Optic Sensor Technologies for Structural Health Monitoring.

Additionally, studies on shape reconstruction and deformation evaluation of flexible structures have demonstrated the high efficiency of FBG sensors in complex-shaped and dynamic systems. This is particularly important for space panels and wing-like structures [81]. Long-gauge FBG sensors have also been successfully applied to accurately measure the vertical displacement of tunnel structures, demonstrating this method's potential in enhancing infrastructure safety.

6. Results and Discussion

This review comprehensively examined the scientific foundations, application domains, and advantages of using FBG sensors for real-time structural deformation monitoring in space infrastructure. The space environment, with its extreme temperature gradients, vacuum, radiation exposure, and mechanical vibrations, imposes stringent requirements on monitoring systems. FBG technology meets these demands and has been proven, through scientific literature and experimental results, to operate with high accuracy and reliability under challenging conditions such as high temperatures, thermal fluctuations, vacuum, gamma radiation, micrometeoroid impacts, and long-term vibration. Real-time monitoring of reusable composite structures, optimization of sensor network density, and integration of sensors into enclosures or multilayer panels enabled the acquisition of reliable structural health data. A key feature of FBG sensors is their multi-parameter measurement capability. A single sensor can simultaneously measure multiple physical parameters (temperature, strain, vibration, pressure, and deformation), allowing complex systems to be monitored with minimal complexity. This is particularly important for pre-flight diagnostics, long-term orbital testing, and emergency response systems. Furthermore, as the sensing mechanism is based on changes in the light wavelength within the fiber, the system is resistant to electromagnetic interference and consumes little power.

Recent advances in AI-augmented multisensor architectures, particularly in UAV threat detection, demonstrate how hybrid sensor networks combined with deep learning models (e.g., CNN-LSTM and attention mechanisms) can enhance robustness against environmental noise and enable real-time decision-making in dynamic conditions. These principles may be adapted to space infrastructure monitoring, where similar challenges of signal interference, rapid deformation, and autonomous response arise.

Furthermore, entropy-based methods for assessing the quality of masking noise interference originally developed for spatial electromagnetic noise generators offer valuable insights into signal randomness and spectral uniformity under high-noise conditions [106]. These techniques, including statistical correlation analysis across frequency subbands, may be adapted to evaluate the spectral stability and noise resilience of optical strain sensor networks in space applications.

Another major advantage of FBG sensors is their small size and lightweight nature, making them ideal for deployment on orbital platforms, rocket-satellite interfaces, solar panels, and wing structures. The ability to conduct spatial multi-point monitoring via sensor networks has significantly broadened their application scope. This enables continuous monitoring of reusable structures, solar arrays, telecommunications satellites, or complex systems such as the International Space Station. The studies reviewed demonstrated that these sensors offer excellent spectral stability, long-term durability, and sensitivity. Their ability to adapt to hostile environments, transmit data reliably over time, and maintain initial calibration parameters highlights the robustness of the technology. In addition to space, FBG sensors have wide applicability in marine, infrastructure, nuclear energy, and geotechnical monitoring sectors. Moreover, recent research on distributed acoustic sensing (DAS) has shown that integrating advanced signal processing techniques such as Fourier and wavelet analysis with machine learning algorithms like LSTM and gradient boosting further enhances the interpretability and performance of fiber-optic systems, particularly in complex environments and emergency monitoring contexts.

7. Conclusion

Ongoing research is increasingly integrating FBG sensors with artificial intelligence algorithms, digital twin models, and autonomous control systems to expand their capabilities. By combining FBG technology with image processing, automated fault detection, real-time diagnostics, and autonomous decision-making systems, structural safety can be fully digitized. Thus, FBG technology presents a reliable, precise, and forward-looking solution for structural monitoring in space infrastructure. Its resilience to harsh conditions, capability for both point and distributed measurements, resistance to electromagnetic interference, and long operational life establish it as a promising tool for structural health monitoring.

Abbreviations:

The following abbreviations are used in this manuscript:

Abbreviation	Full Term
FBG	Fiber Bragg Grating
SHM	Structural Health Monitoring
OFS	Optical Fiber Sensor
DOFS	Distributed Optical Fiber Sensor
WDM	Wavelength Division Multiplexing
UV	Ultraviolet
AI	Artificial Intelligence
MLI	Multi-Layer Insulation
PDMS	Polydimethylsiloxane
CFRP	Carbon Fiber Reinforced Polymer
MZI	Mach–Zehnder Interferometer
FP	Fabry–Pérot
LVDT	Linear Variable Differential Transformer
PWM	Pulse-Width Modulation
SNR	Signal-to-Noise Ratio
RMS	Root Mean Square
LoRa	Long Range
SMF	Single Mode Fiber

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