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Sensors and Systems for Space Applications

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This special section of *Optical Engineering* is devoted to recent advances in sensors and systems for space applications.

The popular appreciation of space weather, orbital debris, and commercial space launch increases the demand for contextual understanding for both challenges and possibilities for the future of space. Developments in microsat and picosat systems, coupled with more affordable launch services, such as the pioneering Space X enterprise, may vastly transform space activities for global communication, knowledge discovery, economic prosperity, and national security. Specifically, sustained excellence in communications, position navigation, and timing is vital to the future conduct of space policies and operations. Toward that end, effective research and development ranges from operational concepts to subsystems and component-level innovations that cover all aspects of the design process, including end-user requirements definition and how those requirements impact design and operational decisions. It is anticipated that the range of scientific and commercial-related topics will also foster multidisciplinary discussions that allow stakeholders to gain an understanding of the technological issues being addressed by their counterparts working in different areas such as: (i) methods of robustness testing for space platforms, (ii) sensors and control for space robustness and autonomous operations, (iii) remote sensing for space intelligence and security, (iv) access assurance and security in space, and (v) optical and quantum information sciences and technologies for flexible and resilient timing, navigation, and communications.[1]

Zhang et al. present recent advances in low-velocity impact testing in hybrid composites for space applications. Low-velocity impact testing is a common, pressing issue in material science because the repercussions are not only hidden but occur often. Carbon fiber-reinforced polymer composites (CFRP) are strong, light weight materials used in everyday products. However, basalt carbon has been gaining traction in more applications as a composite polymer manifested by its mechanical tolerance. Out of all the methods of material testing, eddy current-pulsed thermography (ECPT) is a growing nondestructive testing (NDT) procedure for emerging modalities. ECPT can detect and characterize subtle defects of low-velocity impacts of both basalt-carbon composite and CFRP multi-layers through electromagnetic induction. To validate the thermographic effects, x-ray computed tomography and ultrasonic C-scan are utilized. To analyze the thermal data, both ultrasonic C-scan and x-ray tomography were utilized to visualize the topography and temperature profiles. The ECPT was chosen as the ideal sensing method for polymer composite testing to ensure the materials robustness of future space satellites.

Chen et al. review the recent advances in manufacturing for temperature gradients in additive processes for space applications. Laser metal deposition (LMD) projects a laser with powdered metal injected through a gas stream to additively fill a surface. Testing examines any correlations between the microstructure traits and temperature to model the temperature gradients of the grain size of the deposition layer. The results indicate that the sensed asymmetric temperature distributions support the thermal cycle curve models.

Sun, Song, and Liu highlight an ensemble of classifiers to improve classification performance. Object classification includes ground-based space object detection, ground-based multi-modal imaging for space launch,[2] as well as methods for remote sensing. The objects to classify correspond to the nearest cluster based on their traits with the result being discounted by their paired weight for each classifier. Using the weights, errors are reduced modeling hard (e.g., probabilistic) and soft (e.g., fuzzy) decision making.

Čierny and Cahoy calibrate orbital beams in laser communications. Nanosatellite designs equipped with more complex instruments for data collection and processing, so the downlink traffic demand can be overwhelming for RF communications. Therefore, laser beams offer larger data throughput as well as minimizing hardware, processing power, and cost. The paper presents calibration techniques to enhance beam pointing on nanosatellite laser downlink terminal for CubeSat. Results demonstrate tracking errors of 16 μradians root mean square error (RMSE) for the two axes, overcoming the requirement of 0.65 mradians using higher downlink data throughput.

Tang, Ye, and Xiao address recent advances for solar cells operating in extreme environments for space applications. While solar cells flourish in everyday environments, they do not thrive in harsh conditions in space, such as ionizing UV irradiation from the sun or any high-energy particles. To solve this, two materials are coupled together to endure harsher conditions along with superior performance: titania

(TiO2) and cerium-doped yttrium aluminum garnet (YAG:Ce). Titania not only prevents UV irradiation but also has greater transmittance within the visible and near-infrared spectrum. YAH:Ce has been used as a spectral downconverter in white-light LEDs, and exhibits other useful commercial properties. Therefore, combining both the YAG:Ce's spectral downconverter capabilities as an all-around protector and enhancer and TiO2's ability to ionize UV more effectively will be a suitable solution for solar cells in extreme conditions.

The vast space domain spans commercial opportunities, scientific discoveries, space intelligence, and international security issues. With very few commercial space regulations, the space domain garners attractive interest from satellite and launch methods. Tracking all of the satellites for space situational awareness will be indispensable in the next wave of innovation. Jia et al. develop a diffusion-based enhanced covariance intersection cooperative space object tracking (DeCiSpOT) filter. The DeCiSpOT utilizes communications requirements while balancing computational complexity between various sensors to protect data integrity when measurements are non-existent or inaccurate. Fundamental to the innovation is integrating the 0–1 weighting covariance intersection with the interactive global nearest neighbor algorithm and probabilistic data association for multiple object tracking. The distributed DeCiSPoT method has reproducible results comparable to the optimal centralized cubature Kalman filter for both single and multiple space object tracking, which is attractive for space-based resident space object (RSO) tracking.

Murray-Krezan, Meng, and Seitzer shine a light on geostationary orbit (GEO) belt debris detection. In the space domain, debris originates from satellites and rockets, which can visually impede telescope users, damage satellites, and block signals from transmitting/receiving. Although only a few thousand objects are accounted for in the geostationary orbit (GEO), most of the GEO belt debris is not quantified in physical size with great certainty. Various models have been developed to estimate the number of GEO belt debris objects based on size within the infrared and visible spectrum. Two methods explore the GEO belt debris population characterization within 30% accuracy using data from the NASA-WISE infrared observational campaigns and MODEST visible waveband campaigns.

Space situational awareness (SSA) innovations in tracking and modeling of resident space objects (RSO) require analysis of data analytics, cybersecurity, and information management. Many conventional space IT platforms are not secured, constantly over worked, not retrofitted easily, and limited in performance especially in decentralized and nonuniform SSA systems. Xu et al. introduce a secure SSA communications method. The blockchain-enabled, decentralized, capability-based access control (BlendCAC), holistically assesses the space domain data, manages robust communications network through the dynamic data-driven application system (DDDAS) paradigm,[3] and utilizes a positive feedback loop to select sensors and distill data to sharpen the accuracy of the model. Due to the efficacy of blockchain technology's capabilities in decentralization and anonymity, BlendCAC brings together virtual trust zones, distributed trustless protocols, and smart contracts Experiments with SSA data using the BlendCAC prototype demonstrate the feasibility of scalability, lightweight, and security for space applications.

The special section highlights developments in space sensing analysis, shedding light on cutting-edge technologies of interdisciplinary research in nondestructive evaluation, image processing, optical engineering, composite materials, additive manufacturing, information fusion, data analytics, sensor design, renewable energy, signal processing, satellite communications (SATCOM), blockchain, and SSA. The prominence of space in supporting daily activities will continue to drive research in sensors and systems for space.

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