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Editorial:

Artificial intelligence in impact damage evaluation of space debris for spacecraft

Weimin BAO[1], Chun YIN[†‡2], Xuegang HUANG[3], Wei YI[†4], Sara DADRAS[†5]
[1]*China Aerospace Science and Technology Corporation, Beijing 100048, China*
[2]*School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*
[3]*Hypervelocity Aerodynamics Institute, China Aerodynamics Research and Development Center, Mianyang 621000, China*
[4]*School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*
[5]*Electrical and Computer Engineering Department, Utah State University, UT 84321, USA*
[†]E-mail: chunyin@uestc.edu.cn; kusso@uestc.edu.cn; s_dadras@ieee.org

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Since the first artificial satellite was launched in 1957, increasing human space activities have led to a deteriorating space debris environment. A huge amount of tiny space debris (from millimeter to micron level) appears in the Earth's orbit, and its hypervelocity impact will cause serious damage to the structure and functional units of the spacecraft, including cabin's outer surface, thermal barrier materials, thermal control coatings, solar panels, pipes, and cables. To ensure the safe operation of spacecraft and the completion of space missions, it is necessary to detect and evaluate the impact damage caused by space debris to provide risk warning and timely repair. Due to the complex outer surface materials of spacecraft and the unpredictability of impact damage events, the collected damage detection data present various complex characteristic information. Traditional damage identification and evaluation methods based on manual extraction of feature parameters have difficulty in accurately describing the above complex feature information. In recent years, the application of artificial intelligence (AI) technology in space debris impact perception, damage detection, risk assessment, etc. has begun to receive extensive attention from scholars and engineers, and some breakthroughs have been made in solving such very difficult engineering and technical problems. However, there are still many difficult problems to be solved in the application of AI technology to deal with the issue of space debris. With this background, several important tendencies have emerged in the use of AI methods for spacecraft damage detection and evaluation.

1. Various AI learning algorithms (such as neural networks and deep learning) are used and combined to effectively detect and classify damage features.

AI learns in a variety of ways, and each learning algorithm is good at solving different problems. Combining multiple AI learning algorithms in different scenarios can improve detection efficiency and classify damage features.

2. Modifications and enhancements to the learning algorithm are explored to perform damage pattern recognition and evaluation more accurately and effectively.

To improve the performance of the learning algorithm, modifications and enhancements are essential. Modifications and enhancements to the algorithm

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[‡] Corresponding author

itself, including the setting of the loss function, optimization of iterative steps, and judgment of termination conditions, will have a significant impact on the performance of the learning algorithm. In addition, the complex learning algorithm network itself has a large number of parameters that need to be optimized. In fact, the optimization method of network parameters has become one of the core factors that determine the performance of the learning algorithm.

3. AI learning algorithms and models should preferably be extended to suit spacecraft damage detection and evaluation systems.

In combination with specific spacecraft damage detection and assessment systems, existing learning algorithms and models can be extended by, e.g., preprocessing the actual input test data to obtain better algorithm iterative calculation results, classifying different damage detection scenarios, applying different optimization modules to obtain better performance comparison test results, and giving reasonable classification criteria for damage assessment results.

4. AI technology is used to analyze the data characteristics of various spacecraft impact damage samples to guide the space debris protection design of spacecraft.

The advantage of AI technology is that it can analyze typical characteristics from a large number of data samples. By analyzing the impact damage samples of various types of spacecraft and according to the detection data characteristics under different impact conditions, researchers can obtain the damage type and damage degree of the spacecraft's space debris protection structure. Therefore, engineers can improve the safety of spacecraft in orbit by optimizing the protective structure of the spacecraft.

5. AI technology is used to model and analyze space debris to realize the monitoring, early warning, mitigation, and removal of space debris to reduce the impact of space debris on spacecraft.

Using AI technology to model and analyze space debris has a stronger expressive ability, which can express complex and qualitative empirical knowledge that is difficult to describe with mathematical formulas. AI modeling can be modified and expanded according to the new understanding of space debris model knowledge, and the system can be more flexible to adapt to new needs. The clearer the modeling and analysis results of space debris are, the more accurate the monitoring, early warning, mitigation, and removal of debris impacts are, thereby greatly reducing the impact of space debris on spacecraft.

In short, spacecraft damage feature extraction and damage assessment are critical to the development of the aerospace industry, and these challenges call for new methods and techniques to stimulate the continuous efforts of aerospace equipment research, pattern recognition, and AI.

In this context, the journal *Frontiers of Information Technology & Electronic Engineering* has organized a special feature on the application of AI in the space environment and spacecraft. This special feature focuses on spacecraft damage detection and assessment methods based on AI learning from detection data, including the hierarchical correlation analysis of spacecraft damage characteristics and detection data, and the construction of spacecraft damage assessment models based on AI analysis methods. After a rigorous review process, five research articles were selected for this feature.

To achieve hypervelocity impact (HVI) vibration source identification and localization, Jiuwen CAO and his collaborators investigated the synchrosqueezed transform (SST) algorithm and texture color distribution (TCD) based HVI source identification and localization using impact images. The SST and TCD image features extracted were further fused for HVI image representation. The optimal selective stitching features $OS_{SST+TCD}$ were derived by correlating and evaluating the similarity between the sample label and each dimension of the features to guarantee more accurate detection and localization. Popular conventional classification and regression models were merged by voting and stacking to achieve the final detection and localization. Finally, the HVI data recorded from three kinds of high-speed bullet striking on an aluminum alloy plate were used for experimentation.

Xuegang HUANG and his collaborators constructed a multi-area damage mining model based on an infrared thermal image sequence to describe damages in different spatial layers. Variational Bayesian inference was used for model parameter calculations to efficiently identify different impact damage types from infrared image data. Furthermore, the image-processing framework was developed by combining the image segmentation algorithm with an energy function and the image fusion method with sparse representation, to eliminate variational Bayesian errors and compare locations of different damage types. In the experiments, the proposed method was used to evaluate the complex damages caused by the impact of the secondary debris cloud on the rear wall of the typical Whipple shield configuration. The effectiveness of the method was verified by experimental results about identifying and evaluating the complex damage caused by HVI, including surface and internal defects.

To meet the requirements of nondestructive testing and quantitative evaluation of spacecraft damage, Jianliang HUO and his collaborators proposed to integrate the idea of mosaicing into the detection method based on infrared thermal imaging nondestructive testing technology to meet the requirement of large-scale detection. They obtained images highlighting damage information through classification and reconstruction of thermal data collected, and proposed a mosaicing scheme to realize the mosaicing of images from multiple detection scenes into panoramic images quickly and accurately. Combined with image segmentation and other image processing methods, the damaged area was marked, extracted, and quantitatively calculated, realizing the localization and quantitative evaluation of the damage information.

Yan SONG and her collaborators studied the distributive characteristics of debris clouds in successive shadowgraphs to enhance the damage estimation accuracy of HVIs on a typical double-plate Whipple shield configuration. Specifically, they made efforts to extract the target movement parameters of a debris cloud from the acquired shadowgraphs using image processing techniques and to construct a trajectory model to estimate the damage with desirable performance. In HVI experiments, eight successive frames of fragment shadowgraphs were processed using a hypervelocity sequence laser shadowgraph imager, and four representative frames were selected to facilitate the subsequent feature analysis. Then, using image processing techniques, special fragment features were extracted from successive images. According to the extracted information, image matching of debris was conducted, and the trajectory of debris clouds was modeled based on the matched debris. Finally, the improved estimation of damage to the rear wall was presented based on the constructed model.

Chun YIN and her collaborators developed the Gaussian mixture model to classify the temperature change characteristics in the sampled data of the infrared video stream and to reconstruct the image to obtain the infrared reconstructed image (IRRI) reflecting the defect characteristics. They designed a multi-segmentation objective function to guarantee the effectiveness of image segmentation for noise removal and detail preservation. That is, a multi-objective optimization algorithm was proposed to achieve a balance between detail preservation and noise removal, and the multi-objective evolutionary algorithm based on decomposition (MOEA/D) was used to ensure the accuracy of damage segmentation. During the segmentation process, detailed information of a damaged area was segmented as much as possible from the material background area to ensure complete defect detection. Simultaneously, it was correctly divided into noise areas to ensure the accuracy of damage detection.

Overall, this special feature covers some research topics closely related to the application of AI in the space environment and spacecraft, ranging from automatic detection and intelligent assessment of impact damage, intelligent modeling and risk prediction, to impact perception. However, in practical engineering applications, there are still many basic theories and technical issues not covered in this feature. We sincerely hope that this feature will inspire researchers interested in these topics, and promote the application of AI technology in the aerospace field.

Finally, we would like to express our special gratitude to the authors and reviewers for their support and valuable contributions to this special feature, the editorial staff, and the Editors-in-Chief Profs. Yunhe PAN and Xicheng LU.

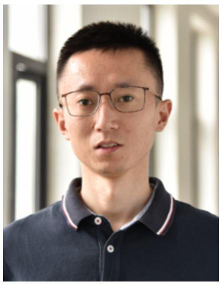
Weimin BAO is an academician of the Chinese Academy of Sciences (CAS) and the International Academy of Astronautics (IAA). He is currently director of the Science and Technology Committee of China Aerospace Science and Technology Corporation, a vice chairman of the 10th China Association for Science and Technology, a member of the Bureau of CAS and the Bureau of IAA, chairman of the Engineering Department of CAS, president of the Chinese Society of Inertial Technology, and dean of the School of Aerospace Science and Technology, Xidian University. He is an academic pacesetter in the field of general and control systems for space launch vehicles in China. He has won the National Award for Progress in Science and Technology (one outstanding and one first-class) and a first-class National Award for Technological Invention.

Chun YIN received her PhD degree from the University of Electronic Science and Technology of China (UESTC) in 2014. She has been a professor of School of Automation Engineering, UESTC since August 2019. She was an associate professor at the School of Automation Engineering, UESTC, from July 2014 to July 2019.

One of her papers has been included in the Top 5 list of Highly Cited Research during 2013–2016 in *J Mechatron*, and one of her papers has been included in the ScienceDirect Top 25 list of Most Download Articles in 2012. She received the Overall Best Paper Award in 2015 IEEE International Instrumentation and Measurement Technology Conference. She serves as a corresponding expert for *Front Inform Technol Electron Eng*. One of her technological achievements obtained the first-class Scientific and Technological Progress Award of Sichuan Province, China. Her research interests include extremum seeking control, multi-objective optimization, infrared thermography testing, and hypervelocity impact engineering.

Xuegang HUANG received his BS degree from Southwest Jiaotong University, China, and his MS and PhD degrees from Mechanical Engineering College, China in 2010 and 2014, respectively. He has been working as an associate research fellow at the Hypervelocity Aerodynamics Institute, China Aerodynamics Research and Development Center since 2014.

His master thesis was selected as one of the Excellent Master Theses of Hebei Province, China in 2012, and his doctoral dissertation was selected as one of the National Excellent Doctoral Dissertations of China in 2017. He has published over 60 refereed journal papers. His research interests include spacecraft measurement and control technology, space shielding engineering, hypervelocity impact engineering, and material dynamic behavior.



Wei YI received his BE and PhD degrees in 2006 and 2012, respectively, both in electronic engineering from UESTC. From 2010 to 2012 he was a visiting student at the Melbourne Systems Laboratory, University of Melbourne, Australia. He was a senior lecturer from 2013 to 2015, and was promoted as an associate professor from 2015 at the School of Information and Communication Engineering, UESTC.

He was the “Best Student Paper Competition-First Place Winner” at the 2012 IEEE Radar Conference, Atlanta, USA, received the “Best Student Paper Award” at the 15th International Conference on Information Fusion, Singapore, 2012, and was a co-recipient of the “Best Student Paper Award” at the 21st International Conference on Information Fusion, Cambridge, UK, 2018. He is an editorial board member of *J Radars* and a guest editor of MDPI *Sensors*. He also serves as a corresponding expert for *Front Inform Technol Electron Eng*. He served as an organizing co-chair, general co-chair, and publication co-chair of ICCAIS 2018, 2019, and 2020, respectively. His research interests include object and signal detection and tracking, radar signal processing, multi-sensor information fusion, and resources management.

Sara DADRAS received her BS degree from Shiraz University, Iran in 2006, and her MS and PhD degrees from Tarbiat Modares University, Iran in 2008 and 2012, respectively, all in electrical engineering. She joined the Electrical and Computer Engineering Department, Utah State University, USA in 2012 as a research fellow.

She is one of the organizers for the SAE Electronics Technical Committee. Currently, she serves as an associate editor for *IEEE Trans Autom Sci Eng*, *IEEE Access*, and *Asian J Contr*. She is a member of IEEE, ASME, and SAE. Her research interests include hybrid electric vehicles, autonomous vehicles, renewable energy systems, image processing, and optimal control.