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Variational Bayesian multi-sparse component extraction for damage reconstruction of space debris hypervelocity impact

Key words: Hypervelocity impact; Variational Bayesian; Sparse representation; Damage assessment

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Motivation

1. The hypervelocity impacts of tiny space debris cause not only visible damage on the surface such as impact craters and impact perforations, but also invisible subsurface damage such as back bulging and spalling.
2. Since this tiny space debris cannot be tracked and cautioned against, the impact event caused by the tiny space debris is extremely harmful to orbiting spacecraft.
3. Based on its high efficiency, ease of visualization, and non-contact advantages, infrared (IR) thermal imaging technology can be employed in the field of aerospace damage detection and evaluation.

Main idea

1. A multi-area damage-mining model is built based on infrared image data, to describe damages in different spatial layers.
2. The variational Bayesian method is employed to calculate parameters in the multi-area damage-mining model, to identify effectively different impact damage.
3. An image segmentation algorithm based on the active contour model and an image fusion method with sparse representation are further used to guarantee the implementation of the hypervelocity impact assessment.

Method

1. To eliminate this coupling and reconstruct the different types of damage from the IR thermal image sequence, the corresponding areas of the different damages are described through their respective characteristic signals.

$$\Psi = \overbrace{\sum_{t_{\mathrm{F}}=1}^{F_{t_{\mathrm{F}}}} X_{\mathrm{F}}(t_{\mathrm{F}})\lambda_{\mathrm{F}}(t_{\mathrm{F}})}^{\mathrm{Dam_F}} + \overbrace{\sum_{t_{\mathrm{B}}=1}^{F_{t_{\mathrm{B}}}} X_{\mathrm{B}}(t_{\mathrm{B}})\lambda_{\mathrm{B}}(t_{\mathrm{B}})}^{\mathrm{Dam_B}} + \overbrace{\sum_{t_{\mathrm{N}}=1}^{F_{t_{\mathrm{N}}}} X_{\mathrm{N}}(t_{\mathrm{N}})\lambda_{\mathrm{N}}(t_{\mathrm{N}})}^{B} + N$$

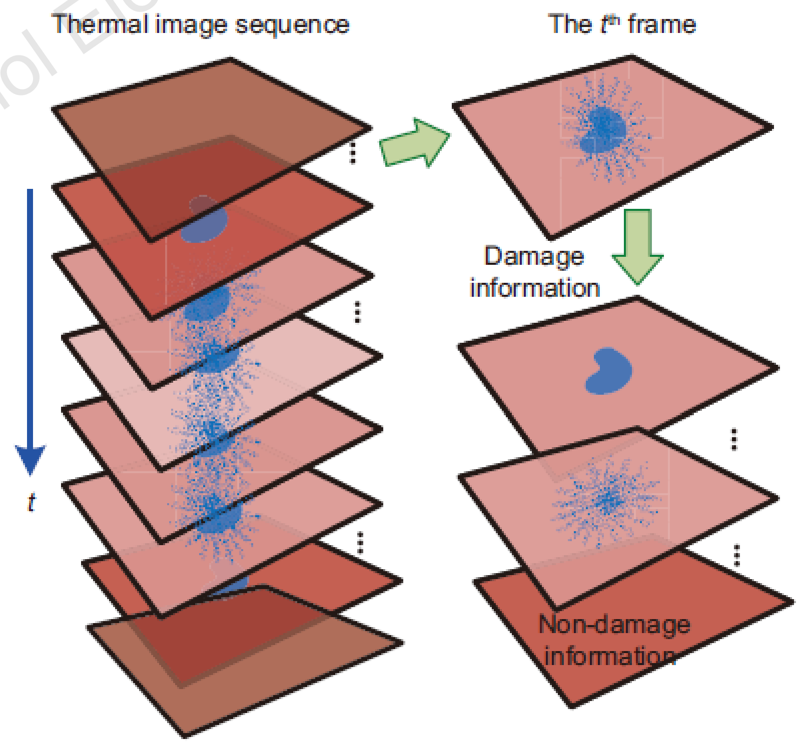


Fig. 4 Possible damages in different layers

Method (Cont'd)

2. To mine the damage features of different areas, variational Bayesian uses the mean field theory (MFT) to estimate the parameters of the multi-area damage-mining model, according to the following formulae:

$$\langle s_{i\star}\rangle^{\mathrm{T}} = \langle \iota\rangle \boldsymbol{\Sigma}^{S} \langle \boldsymbol{T}\rangle^{\mathrm{T}} (\psi_{i\star} - \mathbf{Dam}_{\mathrm{F}_{i\star}} - \mathbf{Dam}_{\mathrm{B}_{i\star}})^{\mathrm{T}}$$

$$\langle t_{j\star}\rangle^{\mathrm{T}} = \langle \iota\rangle \boldsymbol{\Sigma}^{T} \langle \boldsymbol{S}\rangle^{\mathrm{T}} (\psi_{\star j} - \mathbf{Dam}_{\mathrm{F}_{\star j}} - \mathbf{Dam}_{\mathrm{B}_{\star j}})^{\mathrm{T}}$$

$$\left\langle \mathrm{Dam}_{\mathrm{F}_{ij}} \right\rangle = \frac{\langle \iota\rangle \left(\psi_{ij} - \langle s_{i\star}\rangle \langle t_{j\star}\rangle^{\mathrm{T}} - \left\langle \mathrm{Dam}_{\mathrm{B}_{ij}}\right\rangle\right)}{\langle \iota\rangle + \langle \varpi_{ij}\rangle}$$

$$\left\langle \mathrm{Dam}_{\mathrm{B}_{ij}} \right\rangle = \frac{\langle \iota\rangle \left(\psi_{ij} - \langle s_{i\star}\rangle \langle t_{j\star}\rangle^{\mathrm{T}} - \left\langle \mathrm{Dam}_{\mathrm{F}_{ij}}\right\rangle\right)}{\langle \iota\rangle + \langle \upsilon_{ij}\rangle}$$

$$\langle \varrho_j\rangle = \frac{K + F_{\mathrm{t}} + 2u}{\left\langle s_{\star j}^{\mathrm{T}} s_{\star j}\right\rangle + \left\langle t_{\star j}^{\mathrm{T}} t_{\star j}\right\rangle + 2v}$$

$$\langle \varpi_{ij}\rangle = \frac{1}{\left\langle \mathrm{Dam}_{\mathrm{F}_{ij}}^2 \right\rangle} = \frac{1}{\left\langle \mathrm{Dam}_{\mathrm{F}_{ij}}\right\rangle^2 + \Sigma_{ij}^{\mathrm{Dam_F}}}$$

$$\langle \upsilon_{ij}\rangle = \frac{1}{\left\langle \mathrm{Dam}_{\mathrm{B}_{ij}}^2 \right\rangle} = \frac{1}{\left\langle \mathrm{Dam}_{\mathrm{B}_{ij}}\right\rangle^2 + \Sigma_{ij}^{\mathrm{Dam_B}}}$$

$$\langle \iota\rangle = \frac{K F_{\mathrm{t}}}{\left\langle \|\boldsymbol{\Psi} - \boldsymbol{S}\boldsymbol{T}^{\mathrm{T}} - \mathbf{Dam}_{\mathrm{F}} - \mathbf{Dam}_{\mathrm{B}}\|_{\mathrm{F}}^2 \right\rangle}$$

Method (Cont'd)

3. The temperature difference among adjacent pixels in the same damages area is small, and the degree of this temperature difference can be measured by variance. To analyze the temperature distribution of the pixel points in the damaged area, the different areas of the same image are segmented by the dividing curve.

Results of noise elimination (materials I and II)

Method (Cont'd)

4. To reduce the calculation time and improve processing efficiency, frames with similar temperature distributions can be merged through preprocessing before the establishment of the dictionary.

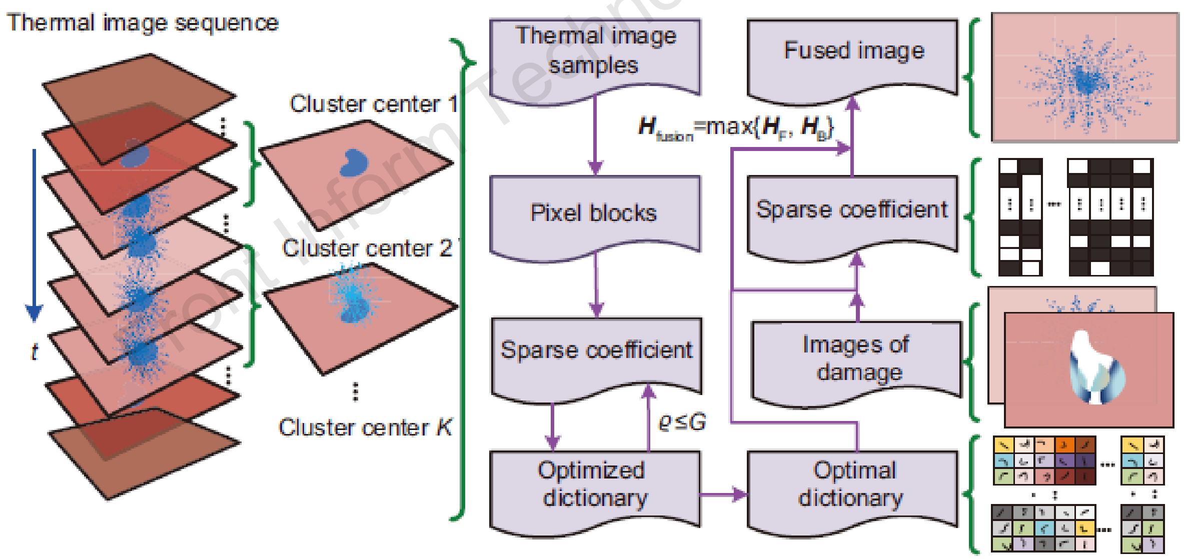


Fig. 5 Image fusion based on sparse representation

Major results

Experimental setup

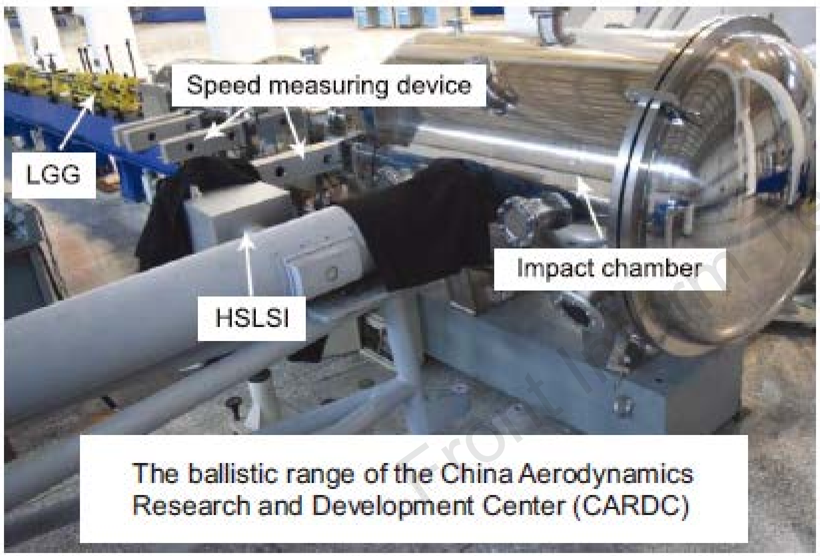


Fig. 6 Setup for the hypervelocity impact experiment

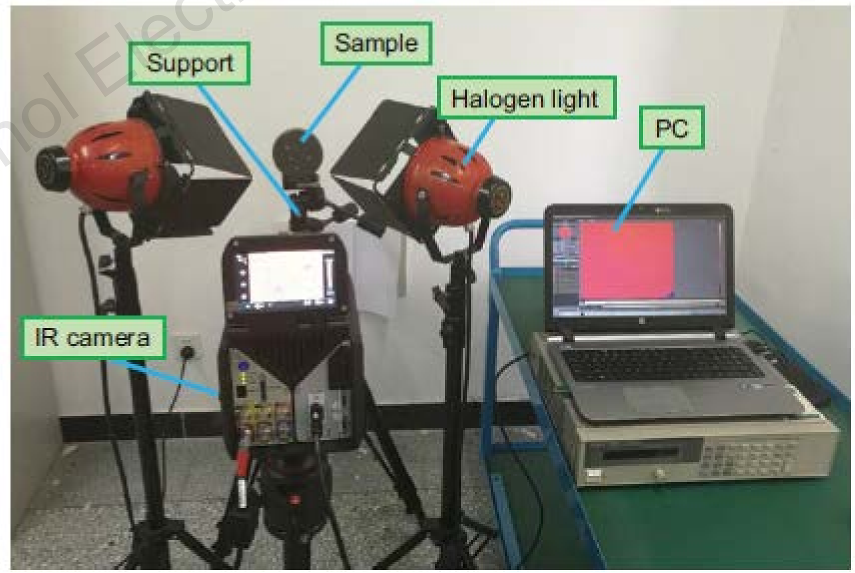
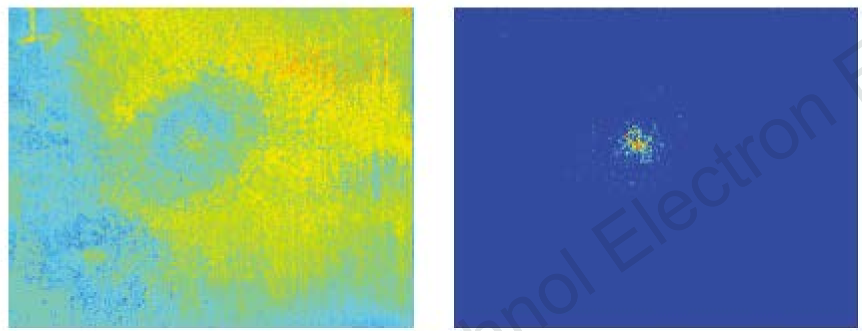


Fig. 9 Experimental setup

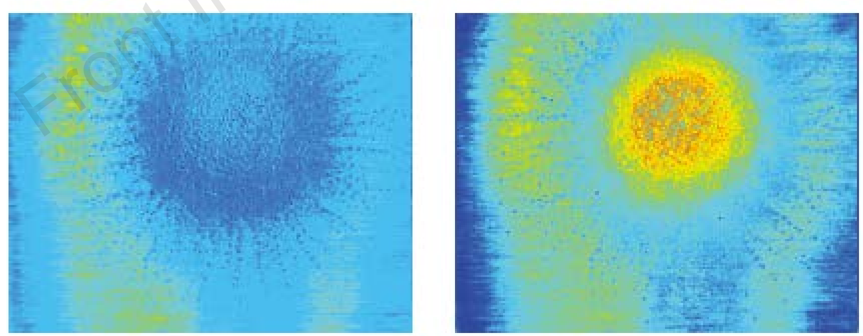
Major results (Cont’d)

Variational Bayesian method



(a) (b)

Fig. 10 Results of the variational Bayesian method (material I): (a) surface; (b) subsurface



(a) (b)

Fig. 15 Results of the variational Bayesian method (material II): (a) surface; (b) subsurface

Major results (Cont'd)

Establishment of the dictionary

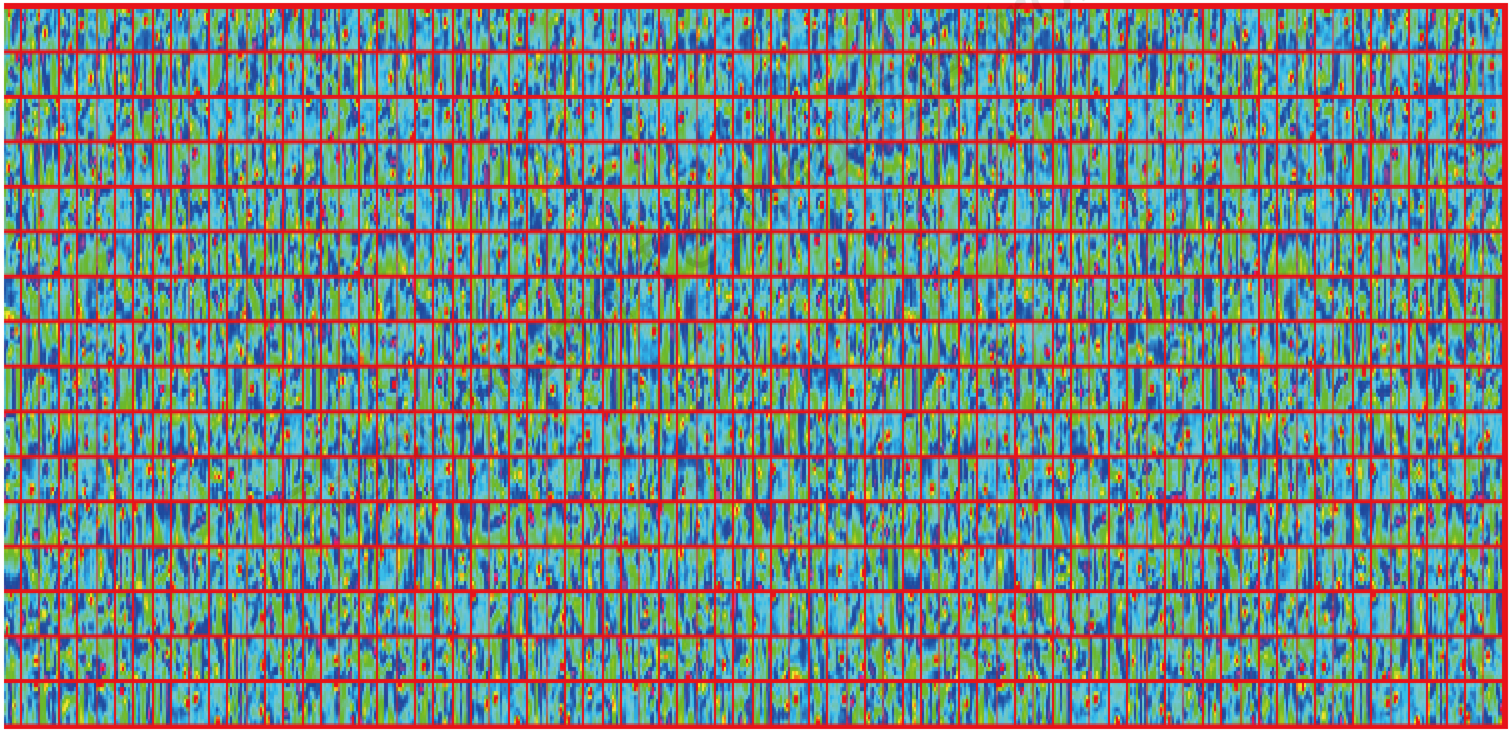
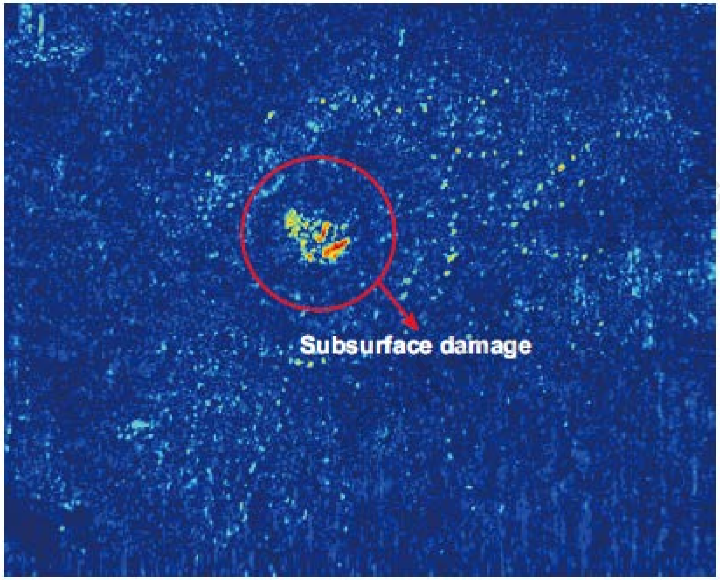
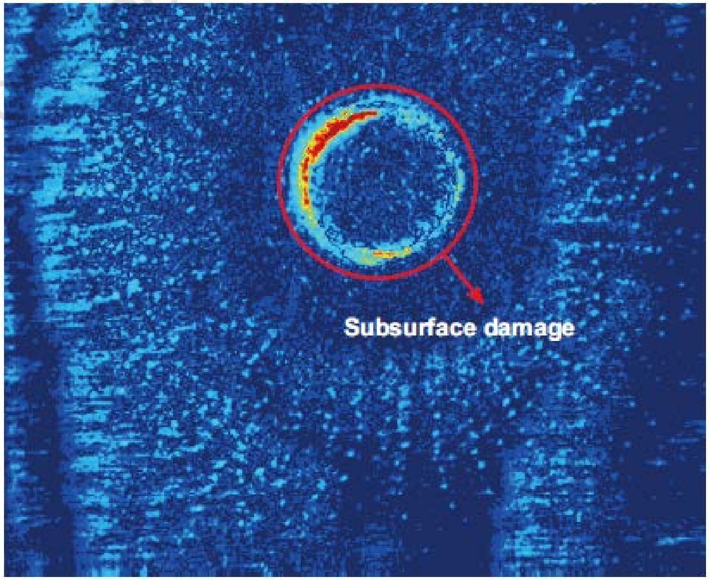


Fig. 13 Dictionary

Major results (Cont'd)

Image fusion





Fused images (materials I and II)

Conclusions

1. To achieve the assessment of the complex damage by hypervelocity impact of space debris, a multi-area damage-mining model has been proposed to extract the different types of damage in IR image sequences.
2. To further visualize the damages using images, the variational Bayesian method has been applied to estimate these parameters of the model.
3. The damage assessment of hypervelocity impact can be completed, by comparing the locations of the different types of damage based on an image-processing framework.
4. Two test samples of a rear wall with hypervelocity impact damages caused by debris cloud were evaluated by the above-mentioned method.

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.