Interactive Diffraction from Biological Nanostructures

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PROBLEM
- Rendering structural colors due to diffraction.
- Using actual measured biological nanostructures.
- At interactive rates.

Challenges are:
1. Modelling the statistical distribution of the height bumps for a "general" nanostructure.
2. Performing complex computations in real-time at high resolution.

RESULTS

- Elaphe nanostructure Diffraction Diffuse texture Diffraction + diffuse
- Different illumination

CONTRIBUTIONS
- A method to render structural colors due to diffraction gratings directly based on physical measurements with atomic force microscopy (No assumptions about the distribution).
- An algorithm for interactive rendering leveraging precomputed look-up tables.

METHOD
- Bi-directional reflection distribution function [1]:
  \[ BRDF_F(\omega, \omega') = \frac{F^{G}}{2\pi A_{\omega}} \left| P \left( \frac{\mathbf{u}}{\lambda} \times \frac{\omega}{\lambda} \right) \right|^2, \]
  \[ Y = \int_{\Delta} BRDF_F(\omega, \omega') S_{\lambda}(\lambda) d\lambda, \]

- Key Ideas:
  - Exploit properties of Fourier transforms to use discrete Fourier transforms.
  - Use spatial coherence length to compute response for non-discrete frequencies.
  - Separate \( \lambda \) and optical geometry related terms.
  - Pre-compute integration over wave spectrum for discretized optical geometry space \((u - v)\).
  - Use relative reflectance for tone-mapping.

VALIDATION
- We validate our method in comparison with an idealized diffraction grating defined by:
  \[ \sin(\theta) = \sin(\phi) + m \lambda / a, \]
  where \( \theta \) is the angle of incidence, \( \phi \) is the viewing angle, \( \lambda \) is a wave frequency and \( a \) is the idealized periodicity of a grating. In our setup, Fig (a) above, \( L \) is the light direction, \( V \) is the viewing direction and \( N \) is the surface normal. \( \omega' \) represents the periodicity. We plot reflectances obtained using our BRDFs at different viewing angles over visible wavelengths. The BRDFs exhibit typical 'peak-viewing-angles' corresponding to idealized gratings with matching periodicities (table below).

<table>
<thead>
<tr>
<th>Data</th>
<th>Estimated Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blazed grating (2500nm)</td>
<td>2500.34</td>
</tr>
<tr>
<td>Elaphe</td>
<td>1144.28</td>
</tr>
<tr>
<td>Xenopelis (Along fingers)</td>
<td>1552.27</td>
</tr>
<tr>
<td>Xenopelis (Across fingers)</td>
<td>605.89</td>
</tr>
<tr>
<td>- Blue curve in Figure (c)</td>
<td>536.13</td>
</tr>
<tr>
<td>- Brown curve in Figure (c)</td>
<td>0.12</td>
</tr>
</tbody>
</table>

A FUTURE DIRECTION
To extend our method for modeling diffraction from other biological nanostructures such as multilayer arrangement on butterfly wings.

REFERENCES

BRDF MAPS
- (a) Shows BRDF maps generated using normal incident light for different viewing directions \((\theta, \phi)\).
- (b) Shows BRDF map for Xenopelis with incident light at an angle of 20°.
- (c) Convergence of the Taylor series with higher values for \( N \) for Elaphe nanostructure.

OBSERVATIONS
- Elaphe Diffraction
- Xenopelis

CONCLUSION
Our approach achieves interactive performance (upto 20 FPS) by precomputing spectral integrals into look-up tables using a Taylor series expansion.