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14. ABSTRACT The broad goal of this project is to develop new computational processes for leveraging visual cues for image-based scene understanding, and we seek to achieve this goal through a careful analysis of reflectance, light transport, and imaging. During the past year, we have continued our exploration of micro computer vision systems, meaning those that can accomplish useful visual tasks within the power and size constraints of micro-scale platforms like micro air vehicles and micro sensor nodes. We have also developed a passive method for					
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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 617-495-4390

Report Title

Physics-based Approaches to Visual Scene Analysis

ABSTRACT

The broad goal of this project is to develop new computational processes for leveraging visual cues for image-based scene understanding, and we seek to achieve this goal through a careful analysis of reflectance, light transport, and imaging. During the past year, we have continued our exploration of micro computer vision systems, meaning those that can accomplish useful visual tasks within the power and size constraints of micro-scale platforms like micro air vehicles and micro sensor nodes. We have also developed a passive method for simultaneous depth and color imaging that exploits a new statistical model of joint spatial and spectral structure in natural images.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

06/01/2013	6.00	Todd Zickler, Ayan Chakrabarti. Depth and Deblurring from a Spectrally-Varying Depth-of-Field, European Conference on Computer Vision. 2013/10/07 00:00:00, . : ,
11/29/2011	2.00	Ioannis Gkioulekas, Sanjeev J. Koppal, Todd Zickler, Geoffrey L. Barrows. Wide-angle micro sensors for vision on a tight budget, 2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 2011/06/19 17:00:00, Colorado Springs, CO, USA. : ,
11/29/2011	3.00	Ioannis Gkioulekas, Todd Zickler. Dimensionality Reduction Using the Sparse Linear Model, Advances in Neural Information Processing Systems. 2011/12/11 17:00:00, . : ,
11/29/2011	1.00	Ayan Chakrabarti, Todd Zickler. Statistics of real-world hyperspectral images, 2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR). 2011/06/19 17:00:00, Colorado Springs, CO, USA. : ,

TOTAL: 4

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

06/01/2013	5.00	Sanjeev J. Koppal, Ioannis Gkioulekas, Travis Young, Hyunsung Park, Kenneth B. Crozier, Geoffrey L. Barrows, Todd Zickler. Towards Wide-angle Micro Vision Sensors, IEEE Transactions on Pattern Analysis and Machine Intelligence (01 2012)
11/29/2011	4.00	Ayan Chakrabarti, Keigo Hirakawa, Todd Zickler. Color Constancy with Spatio-Spectral Statistics, IEEE Transactions on Pattern Analysis and Machine Intelligence (11 2011)

TOTAL: 2

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Ayan Chakrabarti	0.30
FTE Equivalent:	0.30
Total Number:	1

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Todd Zickler	0.08	
FTE Equivalent:	0.08	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PhDs

NAME

Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Scientific Progress and Accomplishments

08/01/2011–09/25/2012

“Physics-based Approaches to Visual Scene Analysis”

Proposal #54262-CS

Todd Zickler

School of Engineering and Applied Sciences
Harvard University

The broad goal of this project is to develop new computational processes for leveraging visual cues for image-based scene understanding, and we seek to achieve this goal through a careful analysis of reflectance, light transport, and imaging. During the past year, we have continued our exploration of micro computer vision systems, meaning those that can accomplish useful visual tasks within the power and size constraints of micro-scale platforms like micro air vehicles and micro sensor nodes. We have also developed a passive method for simultaneous depth and color imaging that exploits a new statistical model of joint spatial and spectral structure in natural images.

1 Micro Sensors

Building on our preliminary results from Year Two of this award [3, 5], we continued our investigation of visual sensors for platforms with severe, micro-Watt power budgets that combine optical processing and complementary post-capture computation. As shown in Fig 1, these sensors are comprised of an array of optical elements, with each element combining a discriminative optical filter and refractive optics to achieve low-power target detection over a wide portion of the hemisphere of light that is visible to a planar sensor array.

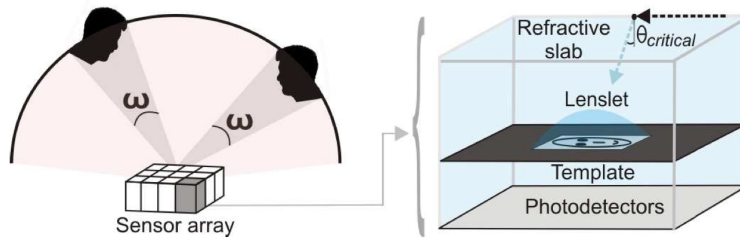


Figure 1: A miniaturized class of wide-angle sensors developed during Year Two of this award. Arrays of these sensors handle specific detection tasks. A refractive slab creates a 180° field-of-view due to Snell’s law. Attenuating templates in the viewing path allow optical filtering and enable vision tasks such as locating edges, tracking targets and detecting faces.

During the past year, we collaborated with Prof. Ken Crozier at Harvard University and Dr. Geoffrey Barrows at Centeye Inc. to design and fabricate micro-scale sensors that combine micron-resolution optical templates with a refractive slab to enable low-power target detection (Fig. 2). We also demonstrated real-time autonomous fiducial target detection on a small autonomous helicopter (Fig. 3). These results are reported in a journal paper that has been accepted to the IEEE Transactions of Pattern Analysis and Machine Intelligence [4]. They also appear online (including videos): <http://www.koppal.com/microvisionsensors.html>.

The journal paper also presents refined mathematical analysis of the sensor design space, including a closed-form solution for optimal sensor dimensions, and a new spherical design that allows spherical optical filtering without distortion.

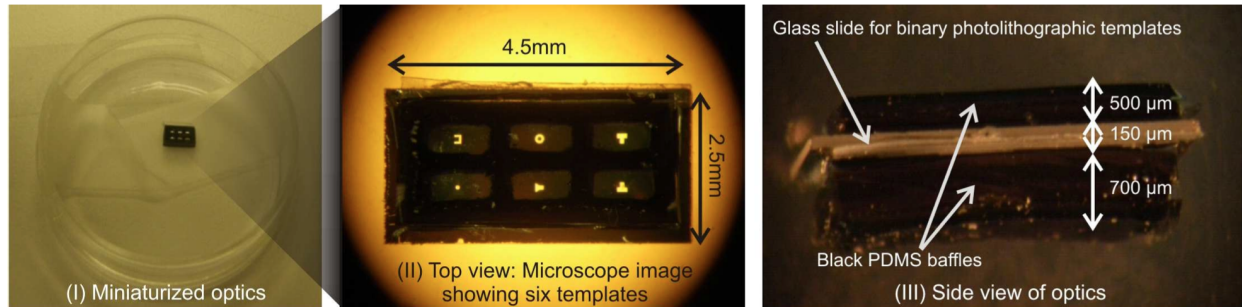


Figure 2: A prototype system for optical filtering with micro-scale templates embedded in a refractive (PDMS) slab, all fabricated with lithographic techniques. *Left*: Array of six optical elements, each with a distinct template and isolated with black baffles, shown in a glass container. *Middle and right*: Close-ups of the top and side of the six-element array taken under a microscope. Details of the fabrication process in are in [4].

2 Passive depth sensing from a spatio-spectral model

In Years One and Two of this award, we devoted significant attention to the task of characterizing the statistical structure that exists jointly in the spatial and spectral dimensions of a natural image. During the current reporting period, we applied insights garnered from this analysis to create a new, passive, image-based depth sensor (*i.e.*, a type of passive RGB-D camera).

As shown inset in the top-left of Fig. 4, we propose modifying the aperture of a conventional color camera so that the effective aperture size for one color channel is smaller than that for the other two. This produces an image where different color channels have different depths-of-field, and from this we can computationally recover scene depth, reconstruct an all-focus image and achieve synthetic re-focusing, all from a single shot. These capabilities are enabled by a spatio-spectral image model that encodes the statistical relationship between gradient profiles across color channels. This approach substantially improves depth accuracy over alternative single-shot coded- aperture designs, and since it avoids introducing

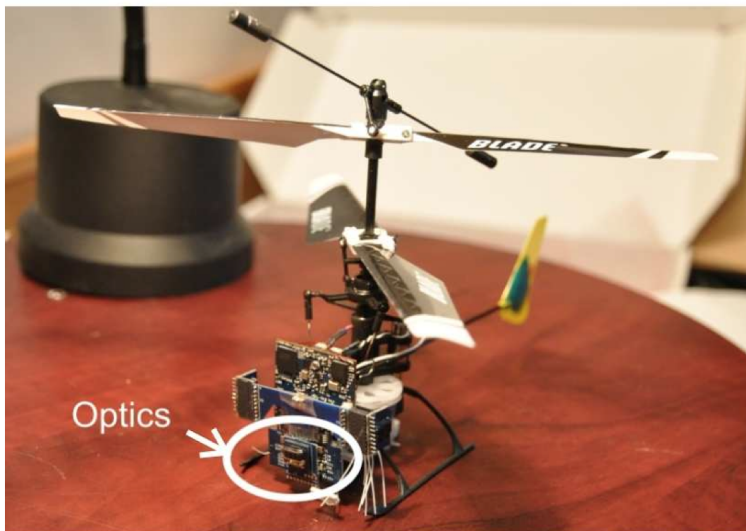


Figure 3: An autonomous helicopter from Centeye Inc., equipped with our optics (Fig. 2) glued to a CMOS photosensor array. With all sensing, processing, and actuation being computed on-board, the system can recognize and respond to simple visual patterns, such as a T-shaped fiducial target. A full video is available at <http://www.koppal.com/microvisionsensors.html>.

additional spatial distortions and is light efficient, it allows high-quality deblurring and lower exposure times.

We demonstrated these benefits with comparisons on synthetic data, as well as results on images captured with a prototype lens, as shown in Fig. 4. The results were reported in a technical report and at the European Conference of Computer Vision [1, 2], and source code is available at <http://vision.seas.harvard.edu/ccap/>.

References

- [1] A. Chakrabarti and T. Zickler. Depth and deblurring from a spectrally-varying depth-of-field. In *Proc. European Conference on Computer Vision (ECCV)*. 2012.
- [2] A. Chakrabarti and T. Zickler. Fast deconvolution with color constraints on gradients. Technical Report TR-06-12, Harvard School of Engineering and Applied Sciences, 2012.
- [3] I. Gkioulekas and T. Zickler. Dimensionality reduction using the sparse linear model. *Advances in Neural Information Processing Systems (NIPS)*, 2011.
- [4] S. Koppal, I. Gkioulekas, T. Young, H. Park, K. Crozier, G. Barrows, and T. Zickler. Towards wide-angle micro vision sensors. To appear in *IEEE Trans. Pattern Analysis and Machine Intelligence*, 2013.

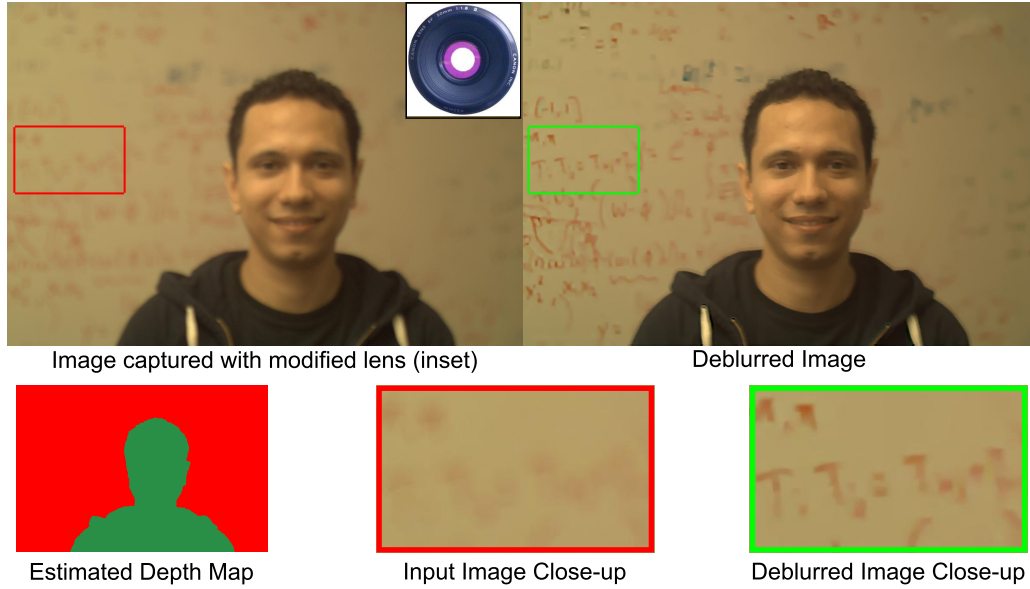


Figure 4: The proposed color-coded aperture generates reliable estimates of scene depth with greater accuracy than color-neutral approaches (no user interaction is required), while simultaneously allowing high-quality deblurring to obtain an all-focus color image that is aligned with the depth map.

- [5] S. J. Koppal, I. Gkioulekas, T. Zickler, and G. L. Barrows. Wide-angle micro sensors for vision on a tight budget. In *Proc. IEEE Conf. Computer Vision and Pattern Recognition*, 2011.