Illumination Optics

Tina E. Kidger
Stuart R. David
Editors

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Andreas L. Timinger, Optics and Energy Concepts AG (Germany)
Teus W. Tukker, Philips Lighting B.V. (Netherlands)

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1 Optimisation
Andreas L. Timinger, Optics and Energy Concepts AG (Germany)

2 Sources and Coupling
Stuart R. David, Optical Research Associates (United States)

3 Applications I
Joshua M. Cobb, Corning Inc. (United States)

4 Applications II
R. John Koshel, College of Optical Sciences, University of Arizona (United States)
Introduction

I would like to invite you all to enjoy the state-of-the-the-art material presented in these proceedings of the first European Illumination Optics Conference.

When I was asked at SPIE Europe Optical Systems Design, Jena (2005) to chair a conference at Glasgow, Scotland in 2008, I agreed and suggested that we should have an Illumination optics conference. Illumination optics, although it has been around for many centuries as an engineering skill, has recently become of much more interest to many engineers and lighting practitioners especially due to the advances in light emitting diodes as illumination sources. The fairly recent development of both CAD and illumination design software, along with hollow, flexible and solid light transmitting waveguides and solid state illumination sources, has added new and exciting interest to illumination design. This excitement is embodied in the material you will find presented in this proceedings volume. The conference and session chairpersons, have received many compliments about the quality and value of the technical content of these presentations and I hope you will find the same to be true for you.

It is my great pleasure to have brought this conference together along with my co-chair, session chairs and committee members and to have so many excellent speakers taking part. I would like to take this opportunity to thank my co-chair, Stuart David, and also the session chairs, John Koshel, Joshua Cobb, and Andreas Timinger, for their work in bringing together such a prestigious group of authors for this conference and hence for this volume.

I wish you every success in understanding, further developing, and creatively utilizing the material in these proceedings for the enhancement it may bring to our global society, your particular area of vocational endeavour, and possibly yourself.

Tina E. Kidger
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Optical system design reliance on technology development

Iain A. Neil

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Glasgow, Scotland, United Kingdom — 2nd September 2008

WELCOME

Firstly, thanks goes to SPIE, the organizing committee, Chairs and Co-Chairs of the Conference for acceptance of this presentation
INTRODUCTION

Before commencing with an outline of the presentation an explanation of the definitions used throughout is given.

DEFINITIONS

1. Technology development is the progression over time of manufactured optical components:
   - Materials ≈ optical substrates
   - Coatings ≈ multi-layer thin films
   - Surfaces ≈ optical surface profiles

2. Optical design software is a tool to apply technology.

3. Optical designer ‘creates’ the optics portion of the optical system design utilizing optical design software to apply technology.

4. FOV is Field of View & NA is Numerical Aperture.
DEFINITIONS (Cont’d)

5 Object is to the left and Image is to the right unless otherwise shown

6 Three wavebands discussed:

- Infrared \( \approx 0.7-1.5, 3-5 & 8-13\mu m \)
  
  \((700-1500, 3000-5000 & 8000-13000\text{nm})\)

- Visible \( \approx 0.435-0.656\mu m \)
  
  \((435-656\text{nm})\)

- Ultraviolet \( \approx 0.434-0.013\mu m \)
  
  \((434.4-13.4\text{nm})\)
EXAMPLE 1.1
PETZVAL OBJECTIVE – SECURITY

Passively Athermalized System
EFL=51mm F/1.5 FOVØ=5° Waveband=8-13µm

EXAMPLE 1.2a
ZOOM TELESCOPE – SECURITY

EXAMPLE 1.2b
ZOOM TELESCOPE – SECURITY

Compact Mechanically Compensated Zoom System
Zoom Ratio=5x Exit Pupil Ø=10mm & FOVØ=72° Waveband=8-13μm

High Efficiency Anti-Reflection Coatings Throughout

EXAMPLE 1.3a
ZOOM TELESCOPE — SECURITY

Compact Optically Compensated Zoom System
Zoom Ratio=9x  Exit Pupil Ø=14.4mm & FOVØ=60°  Waveband=8-13µm

High Efficiency Anti-Reflection Coatings Throughout


EXAMPLE 1.3b
ZOOM TELESCOPE — SECURITY

Key Technology

- MATERIAL
- COATING
- SURFACE
- BENEFITS
- COMPACT
- SIMPLE MECHANICS
- ISSUES
- FOCUS DRIFT THROUGH ZOOM
- ASPHERIC COST
EXAMPLE 1.4
OBJECTIVE — SECURITY

Passively Athermalized & Color Corrected Air Spaced Doublet with Diffractive Surface
Waveband=8-13\textmu m (possibly 3-5\textmu m depending on materials)

ZnS  GaAs

Ge

Diffractive Surface


EXAMPLE 1.5a
ZOOM OBJECTIVE — SECURITY

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EXAMPLE 1.5b
ZOOM OBJECTIVE – SECURITY

Compound Zoom System
Zoom Ratio=180x EFL=6.7-1201mm F/2-5.84 FOV=64.5-0.4°
Wavebands=3-5μm or 8-13μm

Multiple Aspheres Throughout
Zoom Groups on Each Side of an Intermediate Image

STARING ARRAY DETECTOR


WAVEBAND 2
VISIBLE
EXAMPLE 2.1
COMPACT CAMERA ZOOM OBJECTIVE – PHOTOGRAPHIC CONSUMER

Zoom Objective System with 2x Zoom Ratio
EFL=35.7-68.5mm F/3.5-6.8 ImageØ=43.2mm Waveband=Visible


EXAMPLE 2.2a
TELEPHOTO OBJECTIVE – PHOTOGRAPHIC CINE
Passively Athermalized & Color Corrected System with Liquid Elements
EFL=693mm F/2.75 ImageØ=28.9mm Waveband=435-656nm

EXAMPLE 2.2b
TELEPHOTO OBJECTIVE — PHOTOGRAPHIC CINE

Quintuplet

Abnormal Dispersion
Crown Glass with
Thermal Coefficient of
Refractive Index in
Opposite Direction from
Standard Glass

Liquid 1
Liquid 2
AI

SPIE Europe
Optical Systems Design
Glasgow, Scotland, United Kingdom — 2nd September 2008

EXAMPLE 2.3a
MACRO FOCUS ZOOM OBJECTIVE
— PHOTOGRAPHIC CINE

THROUGH ZOOM
(INFINITY FOCUS)

SHORT FOCAL LENGTH

LONG FOCAL LENGTH

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Optical Systems Design
Glasgow, Scotland, United Kingdom — 2nd September 2008
EXAMPLE 2.3b
MACRO FOCUS ZOOM OBJECTIVE
- PHOTOGRAPHIC CINE

THROUGH FOCUS
(SHORT FOCAL LENGTH)

INFINITY FOCUS

CLOSE FOCUS

Close Focus Object/Image Height Ratio = 2.6:1 (At Long Focal Length)

EXAMPLE 2.3c
ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

Macro Focus Zoom System with 3.5x Zoom Ratio
EFL=14.5-50mm  F/2.2  ImageØ=28.9mm  Waveband=455-644nm

KEY TECHNOLOGY
- MATERIAL
- COATING
- SURFACE
- BENEFITS
- VERSATILE
- FIXED FOCAL LENGTH OPTION
- ISSUES
- COMPLEX MECHANICS
- ASPHERE
- COST

EXAMPLE 2.4a

ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

THROUGH ZOOM
(INFINITY FOCUS)

LONG FOCAL LENGTH

SHORT FOCAL LENGTH

EXAMPLE 2.4b

ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

Compact Zoom Objective System with 4.7x Zoom Ratio
EFL=19-90mm F/2.7 ImageØ=27.8mm Waveband=455-644nm

10 Abnormal Partial Dispersion Glasses

Aspheres

EXAMPLE 2.5
OBJECTIVE – PHOTOGRAPHIC PROSUMER

Telephoto System with Diffractive Surface
EFL=780mm  F/5.8  ImageØ=43.2mm  Waveband=435-656nm


EXAMPLE 2.6a
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

THROUGH ZOOM
(INFINITY FOCUS)

SHORT FOCAL LENGTH
7mm

LONG FOCAL LENGTH
2100mm

Intermediate Image

20x Zoom Ratio
16x Zoom Ratio
EXAMPLE 2.6b
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

THROUGH FOCUS
(SHORT TO LONG FOCAL LENGTH)

SHORT FOCAL LENGTH
CLOSE FOCUS

LONG FOCAL LENGTH
INFINITY FOCUS

Close Focus Object/Image Height Ratio = 1.33:1 (At Long Focal Length)

EXAMPLE 2.6c
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

Compound Zoom System with 300x Zoom Ratio
EFL=7-2100mm F/2-13 ImageØ=11mm Waveband=Visible

18 Abnormal Partial Dispersion Glasses

Aspheres

ELECTRONIC DETECTORS

3 Channel Prism Beamsplitter


SPIE Europe Optical Systems Design
Glasgow, Scotland, United Kingdom – 2nd September 2008
EXAMPLE 3.1

PROJECTION RELAY LENS – MICROLITHOGRAPHIC

All Refractive Projection System
RELAY=5:1  NA=0.57  ImageØ=31.2mm  Wavelengths=193, 248 & 365nm

EXAMPLE 3.2

PROJECTION RELAY LENS – MICROLITHOGRAPHIC

Refractive/Reflective Projection System
RELAY=4:1 NA=0.45 ImageØ=30mm Wavelengths=240-256nm

![Version 1 Cube Beamsplitter]

VERSION 1

All Spherical Surfaces
(Larger NA possible with Aspheres)

![Version 2 Plate Beamsplitter]


Glasgow, Scotland, United Kingdom – 2nd September 2008

EXAMPLE 3.3

PROJECTION RELAY OPTICS – MICROLITHOGRAPHIC

All Reflective Projection System
RELAY=4:1 NA=0.25 ImageØ=31mm Wavelengths=13.4nm & <200nm

![6 Mirrors with 6 Aspheres]


Glasgow, Scotland, United Kingdom – 2nd September 2008
EXAMPLE 4.1
OBJECTIVE – SECURITY

Dual Waveband System
F/4.5(elev), F/1.5(azim) & F/2.3(average) FOVØ=40°(elev.) & 53°(azim.)
Wavebands=Visible & 8-13µm


KEY TECHNOLOGY
- MATERIAL
- COATING
- SURFACE
- BENEFITS
- COMPACT
- SOLID STATE
- ROBUST
- ISSUES
- ASHERE COST

-25 mm
EXAMPLE 4.2a
OBJECTIVE – SURVEILLANCE
Compact Multi-waveband Wide Angle Objective
FOV 15°- 80° x 360°
Wavebands=Visible, 0.7-1.5μm & 3-5μm

SINGLE SYSTEM

Aspheres
ZnS Elements
Beamsplitter
Visible & 0.7-1.5μm Detector

FOV 15°- 80° x 360°
PATENT PENDING

EXAMPLE 4.2b
OBJECTIVE – SURVEILLANCE

New Blind Region

Blind Region

'igloo' FOV
20°- 90° x 360°

Blind Regions

PATENT PENDING
EXAMPLE 4.2c

OBJECTIVE – SURVEILLANCE

DUAL SYSTEM

Unobscured
Hemispherical FOV
180° x 360°

FIG. 10

EXAMPLE 4.2d

OBJECTIVE – SURVEILLANCE

QUAD SYSTEM

Unobscured
Global FOV
360° x 360°
KEY TECHNOLOGY SUMMARY

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<th>ULTRAVIOLET</th>
<th>MULTI</th>
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<td>✓ ✓ ✓</td>
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CONCLUSION

- Usually technology provides ‘improvements’ but occasionally it is ‘disruptive’ in that it dramatically changes the optical system design such as enabling a new form of design.
- In the specific case of disruptive technology this usually appears to happen separately in either materials, coatings or surfaces.
- No apparent trend in technology development except:

  “Necessity is the mother of invention”

  Plato c. 400 BC
ACKNOWLEDGEMENTS

Thanks goes to the following individuals for contributions to this presentation

David W. Samuelson
David M. Williamson
Andy Wood
A Perspective on the Design of Head-Worn Displays

Jannick Rolland with
Ozan Cakmakci, Florian Fournier, and Sophie Vo
CREOL, The College of Optics and Photonics
the University of Central Florida

http://odalab.ucf.edu
jannick@odalab.ucf.edu

Highlights

Introduction
Applications
Prior Work

Early work at ODALab

Current Technologies under Development
Head-mounted Projection Displays (HMPD)
Eyeglass Head-Worn Displays (HWD)
Why Head-Worn Displays?

Assuming HWDs can be designed aesthetically (which is not a given) to meet with social acceptance:

- **Mobility**
- **Privacy**
- **Constancy:** Provides the basis for novel user interfaces that are available constantly (on a demand basis) to the user

---

Science Fiction Sets Expectations of Where we Aim to Be Going!

---

Medical Rooms of the Future

Telemedicine: Face to Face Teleportal

Fig 1. Vision of “see-thru-my-eyes” capability: (1) Doctor in local control room guides (2) remote treatment via stereoscopic see-thru headset worn by emergency technician.

Fig 2. Vision of mobile “Face-to-Face” interaction: (1) remote team member wearing 3D face recording system talks to (2) team leader in control center.

Courtesy of Frank Biocca, MSU
Wearable Displays: A Range of Possibilities

Their future lies in large part in their “seamless” integration with tangible interfaces around us.

Augmented Reality / Mixed Reality Vs. Virtual Reality (full immersion)
Augmented/Mixed Reality

Optical See-through

Video See-through

Historical Notes
First graphics-driven HWD was developed by Ivan Sutherland in the 1960s.
Some applications call for optical see-through capability
**Highlights from Past Development**

- U.S. Army first to fly a helmet-mounted sighting system on the Cobra helicopter.

- IHADSS (Integrated Helmet and Display Sighting System) was then deployed by the U.S. Army for the AH-64 Apache Helicopter.

IHADSS, while monocular, greatly contributed to the proliferation of all types of HMDs.

The success of HWD design is most likely to occur when developed

- In the context of the users and
- Targeted at specific applications

**A Main Design Trade-off**

FOV vs. Resolution - Currently limited by microdisplays

Angle subtended by a pixel = \( \frac{FOV}{\text{# of pixels}} \)  

Human eye 1 arcmin

**Approaches:**

1) High-resolution area of interest or inset

2) Partial binocular overlap (“Luning”)

3) Optical tiling  (Kaiser, Sensics)

Recent developments by Sensics.
Driven by Medical Visualization: VRDA Tool
“Virtual Reality Dynamic Anatomy”

NIH - First Award 1997-2002

Methods
Optics, Computer Vision, and Graphics

Our Custom Algorithms
Development of a Kinematic Model of Joint Motion (Baillot, Rolland et al., 2000)

Early Feasibility Experiments
First results in dynamic optical superimposition on an optical bench system

Featured in Scientific American, April 2002

Baillot et al., Presence 2000; Argotti et al., Computers & Graphics 2002
Visualization (Head-Worn Displays)

C. Fidopiastis, L. Davis, J. Covelli, L. Nguyen, R. Martins, O. Cakmakci

Students: F. Hamza-Lup, A. Santhanam

Fig. 5: HMPD is used in a deployable Augmented Reality Centre (ARC): (A) Schematics of the HMPD optics; (B) user wearing a HMPD; (C) the ARC; and (D) user interacting with 3D models in the ARC. (View this art in color at www.dekker.com.)

Eyepiece versus Projection HMDs

**Eyepiece Optics (HWD)**

- **Advantage**
  - Simple/Robust
  - Color
- **Challenge**
  - Optical weight scales with FOV
  - Distortion (electronic comp)
  - Illumination limited (miniature display)

**Head Mounted Projection Display**

- **Advantage**
  - Simple/Robust
  - Color
  - Optics size does not scale with FOV
  - Lightweight
  - Distortion free
  - Lower aberrations than eyepiece design
- **Challenge**
  - Illumination limited by microdisplays
  - Screen type and location
Review of “Large FOV” Eyepiece Optics Design
Rolland and Hua, 2005
Encyclopedia of Optical Engineering (Marcel Dekker)

Related Work

Resolution ~2 arcmins
FOV ~30 degrees
10 mm pupil [Lumus]

Kasai, Int. Symp. Wearable Computers '00.
SONY

AHMD (Advanced HMD)
Ultrawide FOV, off-axis design

Courtesy of LINK/ZYGO and Optical Research Associates
Early 2000

Spatial Uniformity Behavior with Freeform Bezier Shapes

Changing the concavity of the shape can improve uniformity without sacrificing efficiency
Deployable Technology
1st Generation HMPD
with VGA LCD microdisplays
Hua, Ha, and Rolland, Appl. Opt. 42 2003

Fisher, 96 Patent
Miniaturization of the Optics
Deployable Rooms

3D Visualization of the Upper Airway
for Training Medics in Emergency
Intubation Procedures

Augmented Reality Visualization

Lung Dynamics
Anand Santhanam, PhD 06

xlvii
**Imaging: Extended Depth of Focus Needed in Catheters**

**PSF through Working Range**

- **Strehl Ratio**
  - 0.827
  - 0.928
  - 0.914
  - 0.959
  - 0.889

Distance from focal point to the outer surface of the exit window:
- ~0.5mm
- ~1.5mm
- ~3mm
- ~4.5mm
- ~5.5mm

Target \( \Rightarrow \) Strehl ratio > 0.8

*Meemon et al., AO 2008*

Coronary OCT image

J. Am. Coll. Cardiol. 2008;47:C69
Bessel Beam vs. Conventional

First Images of biological tissue acquired with a microlens axicon in a double pass OCT: Images of African frog (Xenopus Laevis) tadpole located at relative axial distances $d$ from each medial position of its depth of focus.

Teleportal Display
UCF/MSU

42° FOV HMPD
Lightweight 595 grams - 2nd Generation HMPD using 800x600 OLED

Optical Design done in the ODALab and
HMPD Optomechanical design done by Nvis Corporation
under SDIR program 2004-2005 with the US ARMY
M-HMPD - Fabric-free, Mobile
Martins, Optics Express 15(22), 2007

See-through, Outdoor
42° FOV

A recent experiment with the MD Anderson Cancer Center Orlando to appear in JDT, Dec08
Comparison of the ARC system with the 2D display system

To appear in Special Issue of JDT, Dec 08

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<th>Experiment 2 (sec)</th>
<th>Experiment 3 (sec)</th>
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<td></td>
<td>ARC</td>
<td>2D monitor</td>
<td>ARC</td>
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</tr>
<tr>
<td>Expert 6</td>
<td>0</td>
<td>3.45</td>
<td>1.40</td>
</tr>
<tr>
<td>Average</td>
<td>0.2</td>
<td>2.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The individual dose beams are delivered to a patient in 30-40 seconds, Thus, a 10 second delay in decision making is highly significant.

Visualization (Head-Worn Displays)

C. Fidopiastis, L. Davis, J. Covelli, L. Nguyen, R. Martins, O. Cakmakci

Students: F. Hamza-Lup, A. Santhanam
Eyeglass Display
Ozan Cakmakci, Kidger Scholarship 05
We Propose to Design Freeform Optical Surfaces whose Representations use Local Basis Functions (as Opposed to Global Polynomials)

- An optical surface can be represented as a sum of basis functions

\[ z(x, y) = \sum \phi_i(x, y)w_i \]

- In matrix form

\[ z = \Phi w \]

- To be invertible, \( \Phi \) must be positive definite, equivalent to having positive eigenvalues.
## Results

<table>
<thead>
<tr>
<th>Surface type</th>
<th>Average MTF</th>
<th>Max. Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anamorphic asphere</td>
<td>26.5%</td>
<td>3.8%</td>
</tr>
<tr>
<td>X-Y polynomial</td>
<td>43.6%</td>
<td>2.65%</td>
</tr>
<tr>
<td>Zernike polynomial</td>
<td>42%</td>
<td>3.74%</td>
</tr>
<tr>
<td>Lin. Comb. of Gaussians</td>
<td>60.5%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Cakmakci et al., Optics Express 16(3) (2008)

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## Revisiting the Dual-Element Design: Pupil Size Expansion

Cakmakci et al. OL (April 2008)

May not be self luminous, thus would require illumination.

Using a 16x16 set of basis functions.
The EyeGlass Display

Won 1st place in the 2007 CTIA Wireless Technology Student Competition.

EyeGlass Display
GENII

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    – N00014-02-1-0261, N00014-02-1-0927, N00014-03-1-0677 ...

• NASA
• Florida Photonics Center of Excellence
• Industry Partners: METI Corporation, NVIS Corporation, Optical Research Associates