Optical Systems Engineering and Endoscope Optical Systems – two lectures

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In previous Lectures in this Engineering Optics for Medical Applications series you learned about:

- Photonic Devices
- Wave Optics
- Geometrical Optics
- Spectroscopy
- Microscopy
- Tissue Optics

In these two Special Topic Lectures we will put all this together in the context of the most used optical system in medicine

- The Endoscope: how it is engineered - and how it is used.

Special Lecture 1 - - Optical Systems Engineering
Special Lecture 2 - - The Endoscope
Lecture 1 - Optical System Engineering

• **Basic Principles of Optics** – the EM spectrum, wave propagation, Snell’s Law, interference & diffraction, photo-electric effect.

• **Image Formation** – Rays and surfaces, paraxial region, thin lenses, thick lenses and principal planes, mirrors, invariants.

• **Aberrations** – Seidel aberrations: spherical, coma, astigmatism, field-curvature and distortion; Chromatic ab’s, stops.

• **Prisms and Mirrors** – Deviation, total internal reflection, different prism shapes and functions.

• **The Eye** – structure, characteristics and defects.

• **Stops and Apertures** – aperture stops, filed stops and vignetting, baffles, depth of field and focus, f/#, filtering.

• **Optical Materials and Interference Coatings** – glasses, plastics, polarizers, reflectors and interference filters.

• **Radiometry and photometry** – Radiance, irradiance, diffuse sources, black body radiation, photometry.

• **Basic optical devices** – telescopes, afocal systems, field and relay lenses, exit pupils and the eye, microscopes, fibers, zoom.

• **Optical Computation** – paraxial rays, meridional rays, skew rays etc, third-order aberrations.

• **Image Evaluation** – optical path difference, aberration tolerances, point-spread and line-spread functions, MTF.

• **General Design of Optical Systems** – camera lenses, symmetry, telescope objectives, diffractive surfaces, computers.

• **Specific Optical Systems** – telescopes, microscopes, cameras, condensers, reflecting systems.

• **Optics in Practice** – manufacturing, specification of tolerances, optical mounting techniques, laboratory measurements.
Endoscopy background

• Probably the most used optical instrument in Medicine.
• Lots of types, all based essentially on the same optical principles and practice.
• Insert a tube into the body –
  - look through it - visually to examine the interior of a hollow organ or cavity inside.

Arthroscopy – orthopedic surgery – knee joints

Bronchoscopy – viewing the bronchial tree and lungs - diagnosis of pulmonary disease

Cardiology – intravascular catheters insides of blood vessels - and the heart

Cystoscopy – urology – bladder tumors, bladder ad kidney stone removal

Fetoscopy – viewing the fetus in the womb

Gastrointestinal (GI) – esophagus, stomach, colon, small bowel and liver, bile duct

Laparoscopy – intra-abdominal organs, biopsies

Neuroendoscopy – perforations of obstructions of ventricles in the brain

Otolaryngology - ear, nose and throat
**Endoscopy** means *looking inside* - and typically refers to looking inside the body for medical reasons using an

**Endoscope**, an instrument used to examine the interior of a hollow organ or cavity of the body.

Unlike most other medical imaging devices, endoscopes are inserted directly into the organ.

A flexible endoscope

A physician using an endoscope

Endoscopic surgery
An endoscope can consist of:

- a rigid or flexible tube
  - [proximal] (nearest) end is looked-into; [distal] (furthest) end is in the patient

- a light delivery system to illuminate the organ or object under inspection. The light source is normally outside the body and the light is typically directed via an optical fiber system

- a lens system transmitting the image from the objective lens to the viewer, typically a relay-lens system in the case of rigid endoscopes or a bundle of fiber-optics in the case of a fiberscope

- an eyepiece – and an additional channel to allow entry of medical instruments or manipulators.

A health care provider may use endoscopy for any of the following:

- investigation of symptoms, such as symptoms in the digestive system including nausea, vomiting, abdominal pain, difficulty swallowing and gastrointestinal bleeding

- confirmation of a diagnosis, most commonly by performing a biopsy to check for conditions such as anemia, bleeding, inflammation, cancers of the digestive system

- giving treatment, such as cauterization of a bleeding vessel, widening a narrow esophagus, clipping off a polyp or removing a foreign object
Introduction to Endoscopy - 3

Endoscopy can review any of the following body parts:

The Gastrointestinal tract (GI tract):
- oesophagus, stomach and duodenum (esophagogastroduodenoscopy), small intestine (enteroscopy), large intestine/colon (colonoscopy, sigmoidoscopy), bile duct: endoscopic retrograde cholangiopancreatography (ERCP), duodenoscope-assisted cholangiopancreatoscopy, intraoperative cholangioscopy, rectum (rectoscopy) and anus (anoscopy), both also referred to as (proctoscopy).

The respiratory tract
- The nose (rhinoscopy)
- The lower respiratory tract (bronchoscopy)

The ear (otoscope)

The urinary tract (cystoscopy)

Endodontic surgery
- Maxillary sinus surgery
- Apicoectomy

The female reproductive system (gynoscopy)
- The cervix (colposcopy)
- The uterus (hysteroscopy)
- The fallopian tubes (fallopocopy)

Normally closed body cavities (through a small incision):
- The abdominal or pelvic cavity (laparoscopy)
- The interior of a joint (arthroscopy)
- Organs of the chest (thoracoscopy and mediastinoscopy)

During pregnancy
- The amnion (amnioscopy)
- The fetus (fetoscopy)

Plastic Surgery

Panendoscopy (or triple endoscopy)
Combines laryngoscopy, esophagoscopy, and bronchoscopy

Orthopedic surgery
Hand Surgery, such as endoscopic carpal tunnel release
Epidural space (Epiduroscopy)
Bursae (Bursectomy)
Introduction to Endoscopy - 4

Endoscope Channels

- Imaging
  - Some have focus control, usually fixed focus with long working distance (low NA, needs strong illumination)
- Illumination
  - Typically a fiber optic bundle
  - Tungsten halogen or arc lamp coupled to fibers
- Water to clean field
- Instrument channels
  - Gas (inflation)
  - Suction
  - Biopsy
  - Cytology brushes
  - Miniature surgical instruments
  - Imaging devices (OCT, fluorescence, or confocal microscopy daughter endoscopes)
# Lecture 2 - Endoscopes

<table>
<thead>
<tr>
<th>Gastrointestinal tract</th>
<th>Upper: pharyngoscopy (pharynx)</th>
<th>Endoscopy (endoscopy of various sections)</th>
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<tbody>
<tr>
<td></td>
<td>pharyngoscopy (pharynx)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td></td>
<td>oesophagogastrroduodenoscopy</td>
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<td></td>
<td>enteroscopy (small intestine)</td>
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<td></td>
<td>colonoscopy (colon)</td>
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<td>sigmoidoscopy (sigmoid colon)</td>
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<td>rectoscopy (rectum)</td>
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<td>proctoscopy (rectum)</td>
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<td>anoscopy (anus)</td>
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<td>capsule endoscopy</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>accessory: cholangioscopy (bile duct)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>Respiratory tract</td>
<td>rhinoscopy (nose)</td>
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<td></td>
<td>laryngoscopy (larynx)</td>
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<td>bronchoscopy (trachea · bronchi)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>Urinary tract</td>
<td>nephroscopy (kidney)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>ureteroscopy (ureter)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>cystoscopy (urinary bladder)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>Female reproductive system</td>
<td>gynecoscopy (cervix)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td></td>
<td>colposcopy (cervix)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>hysteroscopy (uterus)</td>
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<td>fallopian ductoscopy (fallopian tubes)</td>
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<td>culdoscopy</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>Closed cavity via incision</td>
<td>laparoscopy  (peritoneoscopy)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>intra-abdominal · pelvic cavity</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>arthroscopy (joint cavity)</td>
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<td>thoracoscopy (pleural cavity)</td>
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<td>mediastinoscopy (mediastinum)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td></td>
<td>coelioscopy (abdominal cavity)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>During pregnancy</td>
<td>amnioscopy (amniotic sac)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td>fetoscopy (fetus)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td></td>
<td>embryoscopy (embryo)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<tr>
<td>Cardiovascular</td>
<td>angioscopy</td>
<td>endoscopy (endoscopy of various sections)</td>
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<tr>
<td>Others</td>
<td>otoscopy (ear)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<tr>
<td></td>
<td>antrososcopy (maxillary sinus)</td>
<td>endoscopy (endoscopy of various sections)</td>
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<td></td>
<td>ventriculoscopy (brain ventricles)</td>
<td>endoscopy (endoscopy of various sections)</td>
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Lecture 2 – Endoscopy - 1

History

• Catheters and a rectoscope - Hippocrates II (460-377 BC)

• ~2000 yrs later – in 1805 Bozzini invented the ‘Lichtleiter’
  (light conductor; candle + dichroic mirror + tubes; great opposition at the time)

• 1910 - Elner used a gastroscope to examine a stomach

• 1912 – partially-flexible gastrosopes. Wolf, 1906; Storz 1945 - made endoscopy practical and widespread.

• 1954 - Hopkins & Kapany (FO endoscope) - and van Heel (coherent fiber bundle) – the fiber optic endoscope revolution
  FO allows for ancillary channels for air, liquids, suction
  --- also forceps, laser-beams etc for therapeutics & diagnostics (eg, spectroscopy)

• 1987 - video endoscopes

• 1990s - wireless endoscopes

H H Hopkins also invented the zoom-lens, the MTF - and suggested a plastic CD-DVD to replace fragile glass
Nitze’s optical system of ~ 1880. A rigid gastroscope, lit by Edison’s filament globe. It was necessary to administer morphine to the patient.

It was the limitations of the Nitze-style approach that motivated Hopkins into fiber-endoscopy in 1954. Hopkins was twice-nominated for a Nobel Prize.
Lecture 2 – Endoscopy - 2
E is the exit-pupil of the eye-piece: i.e., location for placement of the observer’s pupil (or camera/detector).

Fiber bundles, >3000 fibers, hexagonal-array.

Very thin, so space for other instruments.
Endoscopes – basic operation - 2

**Illumination**

Total amount of light captured from a uniformly illuminated diffuse surface:

$$\Phi = L R (\pi y_o^2) (\pi \sin^2 \alpha)$$

$$\sin(\alpha) = p/z \quad \text{from geometry}$$

Therefore:

$$\Phi = \pi^2 L R y_o^2 (p/z)^2$$

Accepted light proportional to $L$ and $z^2$

$$H = n \sin(\alpha) y_o$$

The optical invariant in object space

$$\Phi = \pi^2 L R (H)^2 / n^2$$

Total light captured is proportional to $H^2$ i.e., to $NA^2$
Advantages of having no fiber bundle as the receiver:

- The number of pixels in an imaging detector is typically greater than the number of fibers in a fiber bundle, giving a sharper image.

- In a conventional fiber-optic endoscope, the hexagonal sampling, which is due to the arrangement of the fibers, is followed by a rectangular sampling through the imaging detector. The mismatch between these two sequential sampling operations makes processing fiber-optic endoscope images difficult.
Endoscopes - Relay Lenses

Conventional

Multiple-lenses combined with rod-lenses to remove aberrations

Hopkins’ rod-lens relay - and variations

Approx Scale:
- 1mm object
- NA = 0.1
- 45 mm length
- 2.7 mm diameter
Endoscopes - Objective Lenses

Many variations

Objective lens with window. Two singlets.

Three elements including a cemented doublet - to remove chromatic aberration

Variable field-of-view

Group II moves to zoom-in on a region of interest; reduced field-of-view
Endoscopes - Prisms

Prisms and assemblies for changing view-directions
Endoscopes – Illumination systems

Light sources such as Xenon

Fibers, Lenses and Light-emitting diodes (LEDs)
Endoscopes – Wireless systems

Capsules

~ 1” long
~ 0.5” diameter
(also polarization and fluorescence optics)

Imaging System: fov ~ 100°

LED Illumination System: veiling glare challenge
Real Images - and what you can see

Colonoscopy

Note:

• Illumination reflections from liquid surface
• Square pixels of the detector/display-screen
Real Images - and what you can see

A complicated psycho-visual problem

We need:

- \( \geq 256 \) gray-levels
- \( \geq \) detector/display rows/columns (\( \geq 16 \)) for target identification
Real Images - and what you can see

<table>
<thead>
<tr>
<th>TARGET</th>
<th>RESOLUTION PER MINIMUM DIMENSION IN LINE PAIRS</th>
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<tbody>
<tr>
<td></td>
<td>BROADSIDE VIEW</td>
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<tr>
<td>TRUCK</td>
<td>0.90</td>
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<tr>
<td>M-48 TANK</td>
<td>0.75</td>
</tr>
<tr>
<td>STALIN TANK</td>
<td>0.75</td>
</tr>
<tr>
<td>CENTURION TANK</td>
<td>0.75</td>
</tr>
<tr>
<td>HALF-TRACK</td>
<td>1.00</td>
</tr>
<tr>
<td>JEEP</td>
<td>1.20</td>
</tr>
<tr>
<td>COMMAND CAR</td>
<td>1.20</td>
</tr>
<tr>
<td>SOLDIER (STANDING)</td>
<td>1.50</td>
</tr>
<tr>
<td>105 HOWITZER</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**AVERAGE**

<table>
<thead>
<tr>
<th>Detection</th>
<th>Orientation</th>
<th>Recognition</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.0 \pm 0.25$</td>
<td>$1.4 \pm 0.35$</td>
<td>$4.0 \pm 0.8$</td>
<td>$6.4 \pm 1.5$</td>
</tr>
</tbody>
</table>

Required resolution for detection, orientation, recognition, and identification.
• A 3D-vision probe for surgeons to see inside the body
  – eg, intestines, colon, nasal and sinus passages

• Stereo-imaging captures picture-pairs, used side-by-side

• Photogrammetry then allows extraction of depth-info from the two images...
  – by using well known relationships between points in image 1 and image 2
  – ie, calculations based on parallax and focal length
3-D Parallax Diagram & Equations

\[ p_c = \frac{fB}{H - h_C} \]
\[ p_a = \frac{fB}{H - h_A} \]
\[ p_a - p_c = \frac{fB(h_A - h_C)}{(H - h_A)(H - h_C)} \]
\[ h_A = h_C + \frac{\Delta p(H - h_C)}{p_a} \]

FIGURE 8-12
Schematic 3D-endoscopy diagrams

Endoscope probe, proof-of-concept 1”, reality ¾” dia.

3D object

Micro-lenses, f = 5mm
60-degree field-of-view

CMOS VGA (or HDTV) chip
Pixel size: 3.5micron (or 1.25 micron)

USB cables

3D Laptop
Auto-stereoscopic
Toshiba Model Qosmio X775

50 – 60 mm range

Fundamental Minimum-Error in Range

= (z/2)/tan(b/2) + (z/2)/tan(c/2)

For lenses spaced 13mm; object at 60mm range:
The limiting range (i.e. height) accuracy is:

VGA ----> +/- 150 microns
HDTV --> +/- 45 microns
Probe/Prototype
Cameras

• Off–the-shelf ‘home’ endoscopes

• VGA: 640 x 480 pixels (1/6” Diagonal)
  – Has LED illumination (adds minor heating)

• Focal length ~ 5mm; 60 degrees fov

• 60mm operating range

• Output to standard USB 2.0 cable

• Plug directly into Toshiba auto-stereoscopic 3D-laptop
Camera
Auto-stereoscopic Display

e, eye separation and window width
i, pixel pitch
l, lenticular pitch
f, focal length
z, distance to viewing windows.
Future work (System enhancements)

- Stereo picture-pair displayed on Toshiba auto-stereoscopic screen for surgeon to see in 3D

- Smaller cameras and probes
  - Smaller pixel size and larger pixel count. Better accuracy.
  - Nasal and head possibilities by miniaturizing to 3mm dia.

- Multiple 3-D views from multiple cameras; composite 3D images

- ‘Surround 3-D’ vision and display
  - Front, back and sideways vision - and display
  - Display cannot be created at present
  - A significant challenge for computer image-science

- Add PDT probe to existing prototype

- Maybe also laser spectroscopy and laser ablation?
Surround-3D camera-geometries

- Imaging all around to the side of the endoscope probe; with overlapping fields-of-view
- Imaging to the front of the endoscope probe
- Imaging to the rear, backwards of the endoscope probe; with overlapping fields-of-view of multiple lenses
- Imaging to the front of the endoscope probe; with overlapping fields-of-view of multiple lenses or fish-eye cameras

Lenses and imaging chips

Electrical outputs to signal processor
Main characteristics of optical endoscopy:

• Reviewed a wide range of optical techniques for endoscopic use
  - objectives, lens relay systems, fibers, illumination, wireless capsules

• Looked at the development of endoscopy from earliest times to the present day

• Looked a little at the future of endoscopy
  - 3D and miniaturization, plus more diagnostics

• Discussed a little about how optical systems engineering makes endoscopy possible
  - some of the challenges - and some routes to solutions
Questions

1. Endoscope illumination and detection calculation

2. Detection and identification of a 1/10th mm polyp
Endoscopy References

Biomedical Optics


Endoscopy


