Computational Challenges for Long Range Imaging

Mark Bray
5th September 2017

BAE SYSTEMS
INSPIRED WORK

Overview

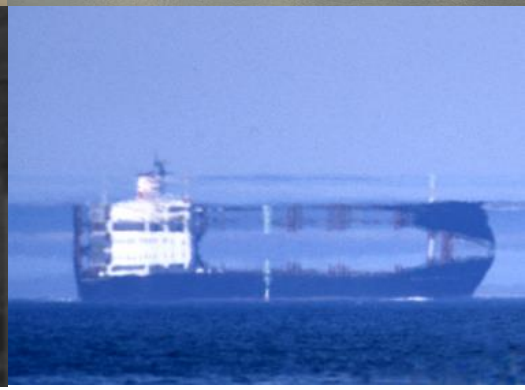
How to identify a person at 10km range?

- Challenges
  - Customer requirements
  - Physics
  - Environment
  - System
- Mitigation toolbox
  - Image quality improvement
  - Other approaches
- Systems considerations
- Conclusions
- Questions for workshop

BAE SYSTEMS
INSPIRED WORK

Specific Challenges

- Customer requirements
  - Cost £££
  - Size, weight and power
  - Real time operation
  - Ease of use
  - Training required
  - Day/night?
  - Platform (e.g. ship, tank, plane?)
- Physics
  - Lens aberrations
  - Diffraction and lens diameter
  - Optical signal to noise power
  - Pointing accuracy and stability
- Environment
  - Illumination
  - Weather
  - Obscurants
  - Turbulence
  - Motion



evansheline.com/2011/02/crazy-huge-camera-lens/ ;

www.leelofland.com/thermal-imaging/

sg.theasianparent.com/singapore-haze-facts-and-precautions/ ;

philippe.boeuf.pagesperso-orange.fr

BAE SYSTEMS
INSPIRED WORK

Specific Challenges

System considerations

- Current status
  - There are multiple mitigation strategies
  - Each has strengths and weaknesses
  - Mitigation strategies have been developed in isolation
  - No single approach will meet challenge
  - Together they could provide a toolbox

- How are the tools best used together?
  - How do tools interact?
  - How to successfully combine tools?
  - How to measure success?

- How to satisfy end-users' needs?
  - How to minimise need for expert operators?
  - Does recognition require a human?
  - If automatic what are image requirements?

westsideinternalmed.com/healthy-toolbox/;

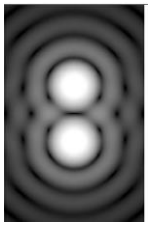
www.dreamstime.com/stock-image-watchmaker-tools-special-repair-clocks-image31386421

www.navsource.org/archives/08/08723.htm

Diffraction

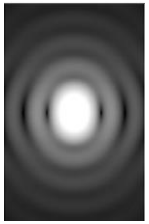
Fundamental resolution limit

https://en.wikipedia.org/wiki/Angular_resolution



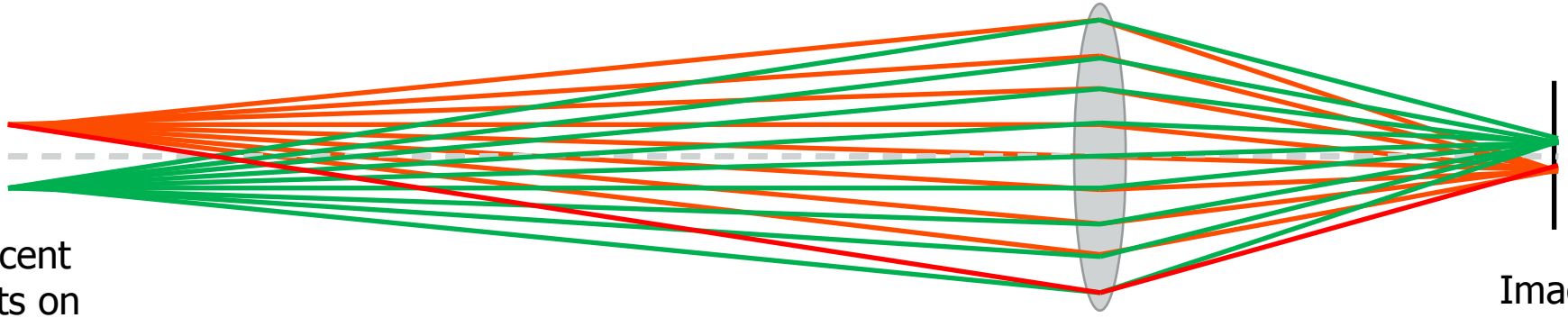
Point Spread Spots well resolved.
D > D1

Point Spread Spots just resolved.
D = D1



Point Spread Spots not resolved.
D < D1

Diffraction Limited
Point Spread Spot Size = ~1.22 λ f/D



Adjacent points on the target subject

Circular Lens diameter D

Image Focal plane

BAE SYSTEMS
INSPIRED WORK

Diffraction estimate

How big a lens is needed?

- Estimates vary for minimum pixel resolution required to recognise a human face
- Here use 1mm resolution for a stranger; and 5mm resolution for a known face
- ➔ 120x120 pixels (stranger); and 24x24 pixels (known)

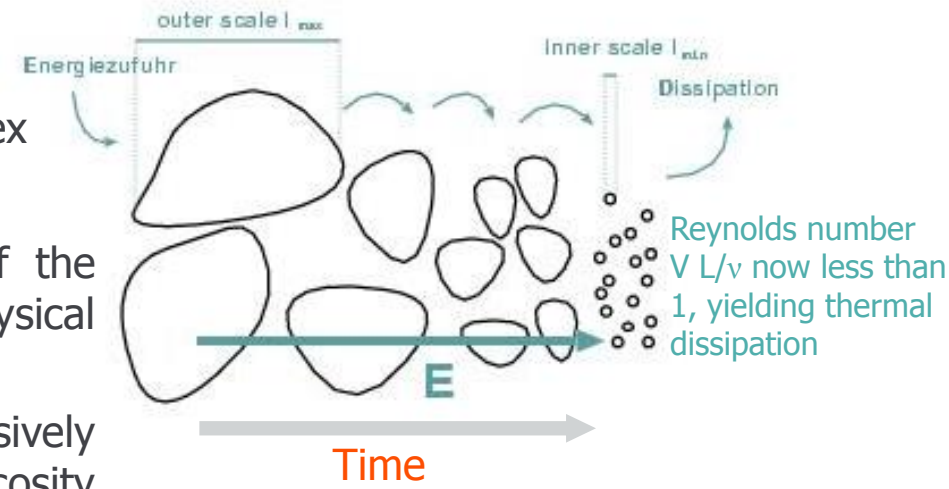
- Objective lens to recognise a stranger at 10km (visible band):
  - ~7.7 m diameter
  - ~5.8 metric-tonnes (Assuming BK7 glass average thickness ~ 5cm)

Subject	Lens diameter @ 1km	Lens diameter @ 10km
Stranger (1mm)	770 mm	7.7 m
Known face (5mm)	154 mm	1.54m
Vehicle (5cm)	15 mm	154 mm
Building (1m)	0.8 mm	7.7 mm

Turbulence

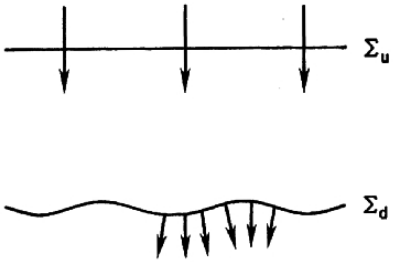
Distortion of image by random refractive index perturbations in the optical path

- Air turbulence is created by heating of the atmosphere, or by wind flow past physical obstacles.
- Kinetic energy is transferred to successively smaller and smaller eddies until viscosity dominates and the energy is converted into heat.
- Turbulent mixing of air different temperature or pressure gives rise to refractive index variations in the air transmission path.
- Familiar as star 'twinkling'
- Resolution due to turbulence improves as $\lambda^{\frac{1}{5}}$



"Observing Through Earth's Atmosphere"; Steven R. Majewski , (2015) Astronomy 5110 Lecture Notes, Virginia University. http://www.faculty.virginia.edu/ASTR5110/lectures/atmos1/turbulence.html

Air turbulence distorts the optical wave front



BAE SYSTEMS
INSPIRED WORK

Turbulence characteristics

Reduces effective aperture diameter of large camera lens

- Atmospheric air turbulence typically reduces the effective optical resolution aperture of a traditional optical imaging system to the Fried Coherence length of the turbulent air r_0 of typically ~2 cm to ~5 cm
- The time evolution of atmospheric turbulence due to Kolmogorov type turbulence is given by the 'Greenwood' frequency which typically ranges from 10s to 100s of Hertz depending on atmospheric conditions.

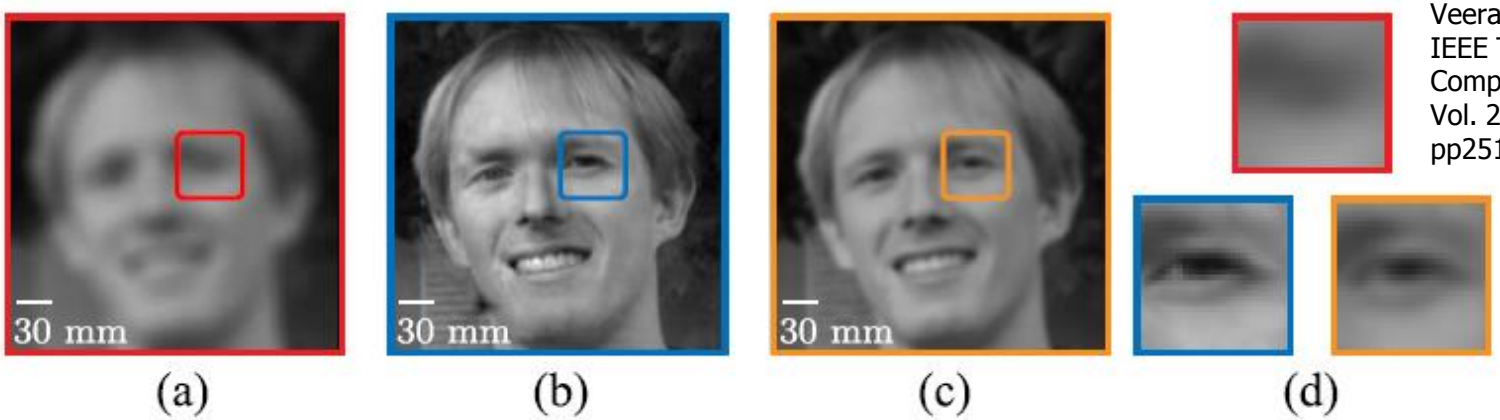
"Robustness of speckle-imaging techniques applied to horizontal imaging scenarios"; Jeremy P. Bos, Michael C. Roggemann; Opt. Eng. 51(8), 083201 (Aug 03, 2012).

Diffraction (finite aperture) mitigation

Synthetic aperture increases effective aperture diameter of camera lens

- Coherent source is used to illuminate scene
- A series of images are collected with motion of camera
- Effective aperture is provided by extreme edges of lens
- Requires:
  - >= 65% overlap of images
  - Coherent illumination source (laser)

"Toward Long-Distance Subdiffraction imaging using Coherent Camera Arrays"; Jason Holloway, M. Salman, Manoj K. Sharma, Nathan Matsuda, Ashok Veeraraghavan; (2016), IEEE Transactions on Computational Imaging, Vol. 2, No. 3, Sept 2016, pp251-265.



Cheap f/16 1200mm & 75mm diameter lens, Passive illumination .

Same cheap f/16 camera lens, Coherent illumination,81 images yielding a 300mm synthetic aperture

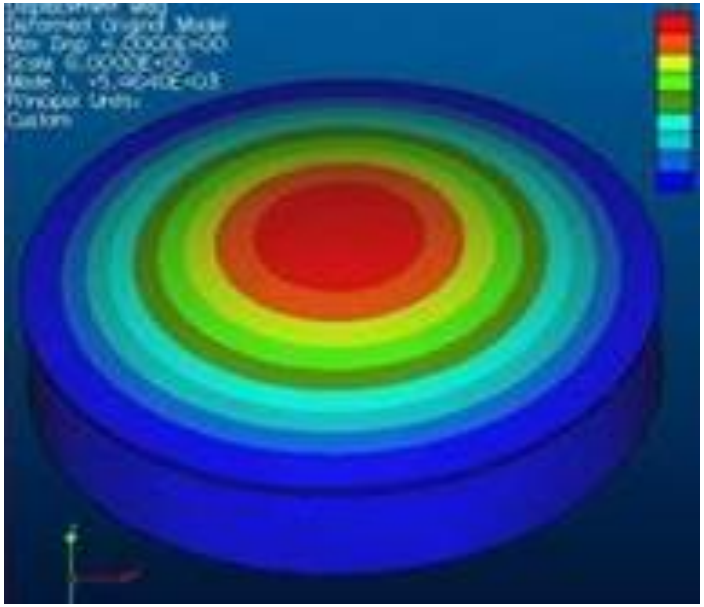
Expensive ($150k) f/5.6 camera1204mm& 215mm diameter aperture Passive illumination

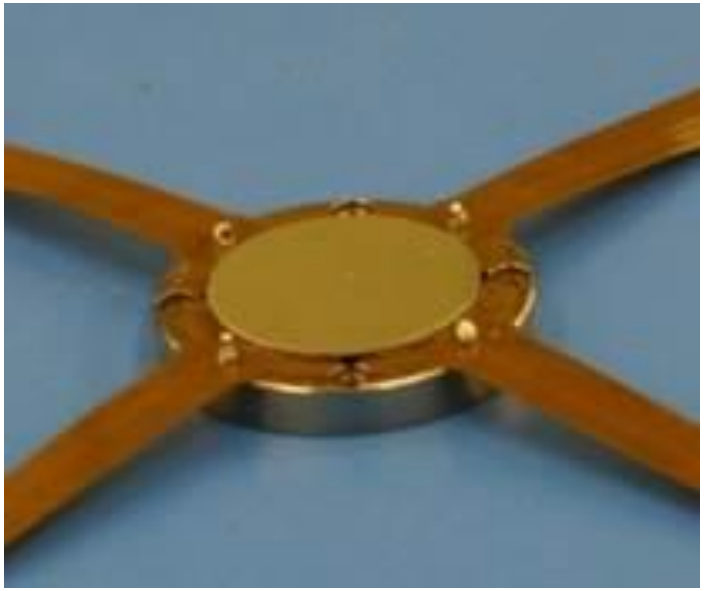
BAE SYSTEMS
INSPIRED WORK

Categories of turbulence mitigation

Techniques

- Pre-detector processing (hardware based)
  - Use additional hardware to process the light before detection (e.g. adaptive optics, wavefront sensing)
- Computational imaging (hardware/software based)
  - use alternative hardware approaches and data processing to compute images (e.g. ghost imaging, plenoptic imaging, multi-aperture imaging)
- Post-detector processing (software based)
  - take images from conventional video or sequences of short exposure images and perform post processing (e.g. deconvolution, lucky imaging, speckle imaging)

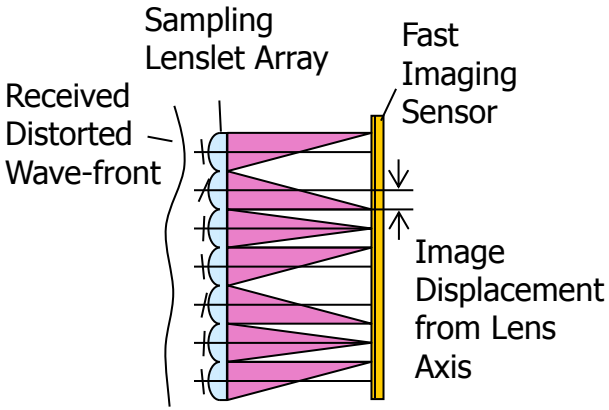




Pre-Compensation Example

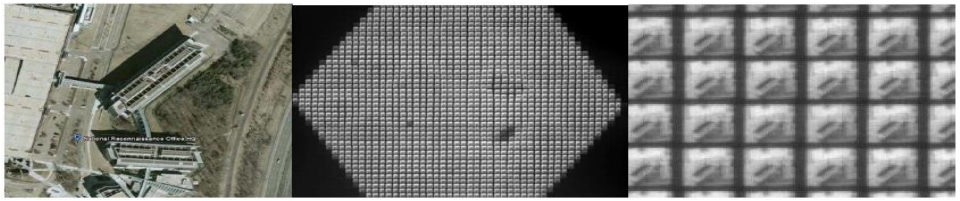
Adaptive-optics using wavefront sensing

- After reflection by adaptive-optic mirror, incoming optical beam split
  - Half to focal plane array
  - Half to lenslet array
- Lenslet array samples wavefront; correlation techniques used to calculate distortion (extended Shack-Hartmann)
- Distortion compensated by deformable mirror



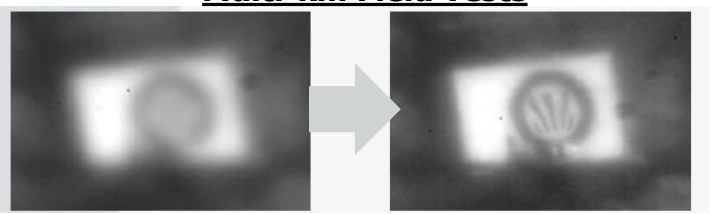
Processing challenges

- Fidelity of wavefront correction using correlation
- Real time operation (bandwidth ~10x Greenwood frequency)



Extended scene Lenslet array Individual lenslet images

Multi-km Field Tests



No compensation Adaptive optics compensation

A Wirth et al, *"Scene based Wavefront Sensing for Figure Control of Airborne and Space Optics"*, ISBN: 978-1-55752-878-0

BAE SYSTEMS
INSPIRED WORK

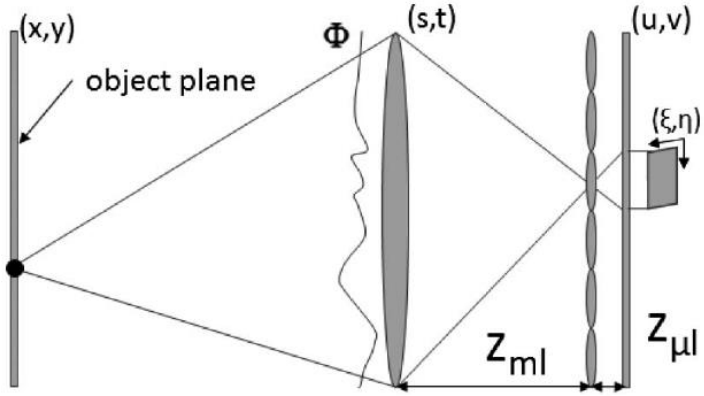
Computational Imaging Example

Plenoptic sensing

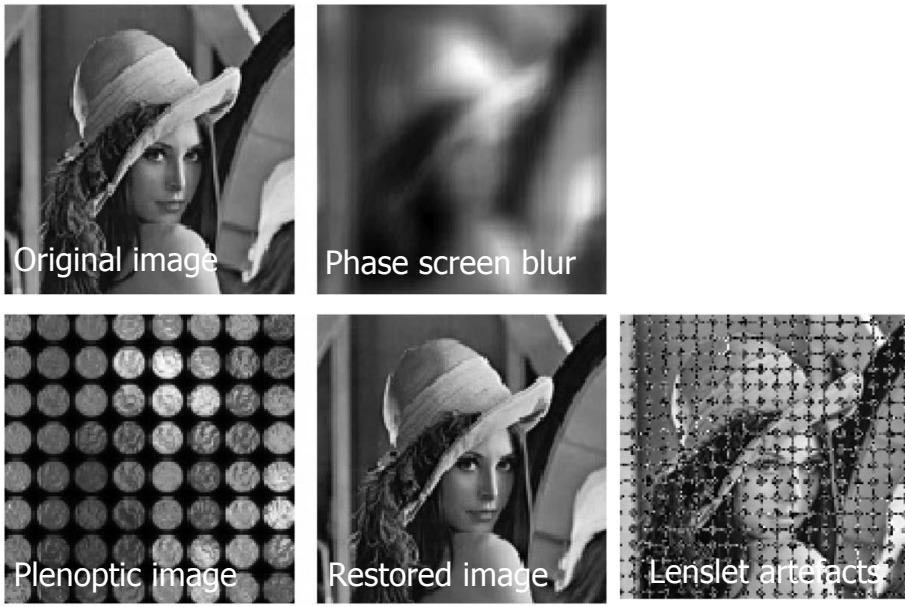
- Uses lenslet array
  - Similar to extended Shack-Hartmann wavefront sensing
- In this case image is focussed onto lenslet array and detector behind samples light field (includes direction of arrival as well as origin)
- Cross correlation of lenslet images can be used to compute wavefront shape
- Deconvolution techniques can be used to create high resolution digital images
- Conventionally used for computational refocus
- Recent developments allow turbulence to be corrected
- Depends on high signal to noise ratios >30dB

Processing challenges

- Fidelity of wavefront correction using correlation
- Real time operation



"*High Resolution Imaging and Wavefront Aberration Correction in Plenoptic Systems*"; J. M. Trujillo-Sevilla, L. F. Rodríguez-Ramos, I. Montilla, J. M. Rodríguez-Ramos; (2014), Optics Letters Vol. 39, No 17, pp 5030 – 5033.



BAE SYSTEMS
INSPIRED WORK

Post-Compensation Example

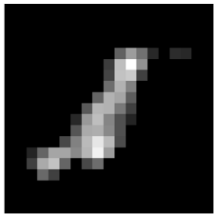
Multi-frame blind deconvolution

- Blind deconvolution is used to deblur images when both the true image and point spread function (PSF) are unknown. Multi-frame blind deconvolution makes the problem less under-determined.
- Uses a sequence of aberrated frames to estimate the PSF and the original object by optimising cost function.
- It can be used with longer exposure images containing blur due to the changing atmosphere.
- Use a variety of optimisation algorithms that find the most likely object and PSF that would generate the set of images.
- In estimating the PSF, this technique has the potential to super-resolve the image.

Processing challenges

- Optimisation target – assumed characteristics of scene, or PSF
- Volume of data
- Real time operation

A Zisserman, '*Lecture 3: Image Restoration*'. http://www.robots.ox.ac.uk/~az/lectures/ia/lect3.pdf



Estimated blur

BAE SYSTEMS
INSPIRED WORK

Other Deconvolution Techniques

- Blind deconvolution
  - The blind deconvolution algorithm can be used effectively when no information about the distortion (blurring and noise) is known.
- Regularized filter
  - A regularized filter can be used effectively when limited information is known about the additive noise.
- Wiener filter
  - Wiener deconvolution can be used effectively when the frequency characteristics of the image and additive noise are known, to at least some degree
- Lucy-Richardson method
  - This function can be effective when the PSF is known but little is known about the additive noise in the image.

G. Archer et al, "Comparison of bispectrum, multiframe blind deconvolution and hybrid bispectrum-multiframe blind deconvolution …", Opt. Eng. 53(4), 043109, 2014

Q. Fan et al, "A multi-parameter regularization model for image restoration", Signal Processing, Vol. 114, pp131-142, 2015

S. Vasudevan, "Image Enhancement and resotration…", Blog, https://sriramvasu.wordpress.com/2017/03/08/image-restorationdeblurring-inverse-filtering-and-wiener-filter/

M. Dobes et al, "Blurred image restoration: A fast method of finding the motion length and angle", Digital Signal Processing 20 (2010) 1677–1686

Is High Resolution Needed? (1)

Could we use other information to reduce resolution requirement?

- Remember challenge was:
  How to identify a person at 10km range?
- Do we need to be able to recognise a face?
  - Humans can be recognised by gait (opposite articles)
- Skin tone?
  - Can hyperspectral skin tone analysis help to identify individual?
  - What about illumination / make-up etc.?

19 September 2012

Ministry of suspicious walks
Could you tell if a phone has been stolen by a change in the walking pattern of the person carrying it? An Android app developed by Carnegie Mellon, uses data from the accelerometer and gyroscope to record the phone's movements as its owner walks. The app can identify a particular gait with over 95 per cent accuracy. The technology could one day be used to shut a device down if it registers a gait that does not match that of its owner.

"face recognition requires reasonably high-quality images… a person's gait can be recognised from low-quality CCTV footage"

BBC NEWS

15 April 2008

How can you identify a criminal by the way they walk?

WHO, WHAT, WHY?
The Magazine answers...

A burglar has been caught because of his bow-legged walk, but how easy is it to catch a criminal by analysing their gait?

John Rigg was both lucky and unlucky when he was caught on CCTV near a house he had burgled.

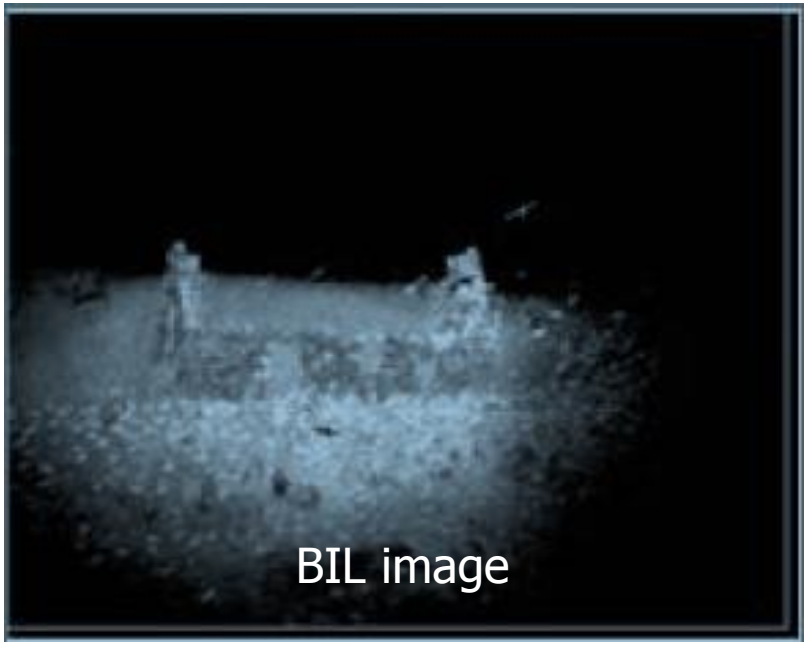
Lucky because it didn't catch his face. Unlucky because the footage showed his walk, which was, to the casual observer, rather like John Wayne's.
...

BAE SYSTEMS
INSPIRED WORK

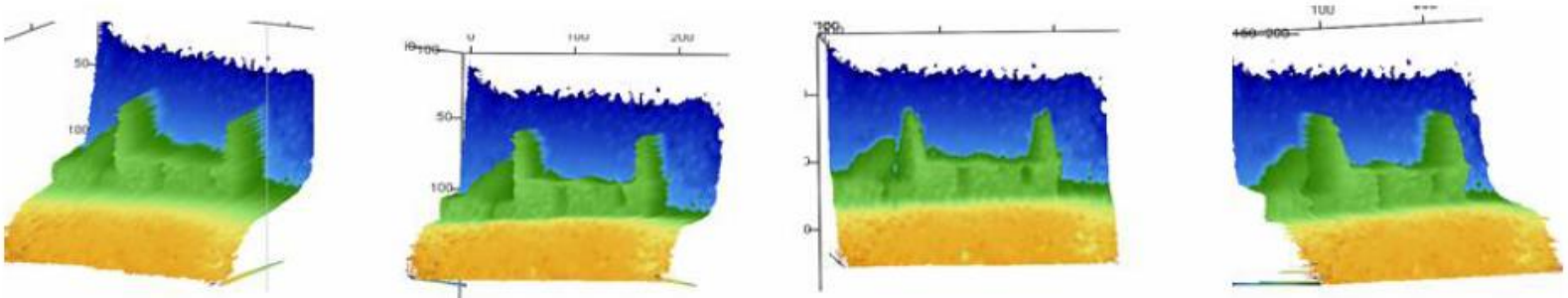
Is High Resolution Needed? (2)

Could we use other information to reduce resolution requirement?

- 3D
  - Can use of extra dimension trade against resolution requirement?
  - Burst illumination LIDAR can be used to derive 3D information about objects via snapshots
  - What information and processing is needed to ID individual?
  - What are camera requirements



I. Baker et al, "Advanced infrared detectors for multimode active and passive imaging applications", Proc. of SPIE Vol. 6940 69402L, 2008



3D image created by 4 gate depths

BAE SYSTEMS
INSPIRED WORK

System Architecture

- Many potential techniques exist
  - Each with its own strengths, weaknesses and requirements
- For each situation we need a tailored blend of techniques
- What is the best architecture to combine the techniques?
  - Single?
  - Serial (in what order)?
  - Parallel (how to fuse results)?
- How to make it fast?
- How can we tune and adapt the individual techniques, and the overall architecture, to give ~~the best~~ a good enough result?
  - How to quantify good enough?
  - How to do tune autonomously?

https://www.smartdraw.com/flowchart/examples/flowchart-example-hiring-process/

Conclusions

Computational Image Processing has a role to play in long range imaging

- Physical limitations
  - Resolution of target at range ultimately limited by aperture of objective lens
  - However turbulence can reduce effective aperture
- Several emerging techniques can be used to compensate for effects
  - Computation needed for all discussed here,
  - …ranging from assisting hardware (e.g. wavefront calculation for adaptive-optics)
  - … to purely software e.g. blind deconvolution
- Solutions <u>must</u> be compatible with end-user requirements e.g. size, weight, power and cost
- … <u>and address end-users' problems</u>
- A systems approach harnessing multiple techniques is needed to maximise the ability to recognise an individual at 10km

BAE SYSTEMS
INSPIRED WORK

Questions for Workshop

System approach needs to be developed

- What is success (good enough)?
  - How do we measure it?
  - What does this mean for system requirements?

- How are the tools best used together?
  - How do tools interact non-linearly?
  - How to successfully combine tools? What order?

- How to satisfy end-users' needs?
  - How to minimise need for expert operators?
  - Can system self-tune for external conditions?
  - How to process in real-time?
  - How can we maximise range of operating conditions?

- How to exceed end-users' expectations
  - Can recognition become autonomous?
  - If so how does this affect image (& imaging system) requirements?

BAE SYSTEMS
INSPIRED WORK

Thank you for your attention

Any Questions?

BAE SYSTEMS
INSPIRED WORK