Fast 3D reconstruction with single shot technology : engineering and computing challenges

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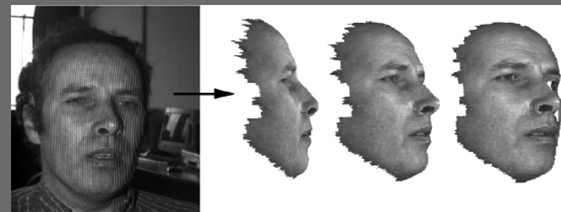

Fast 3D Reconstruction with Single Shot Technology: Engineering and Computing Challenges

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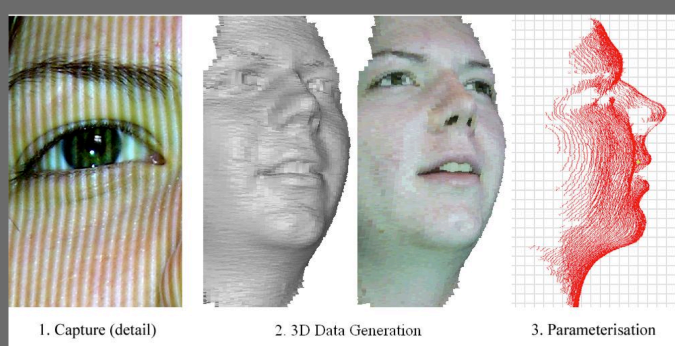
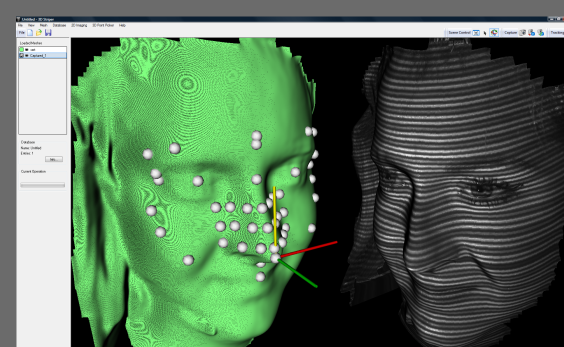
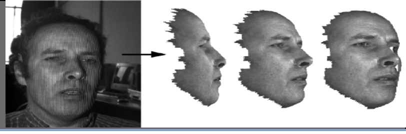
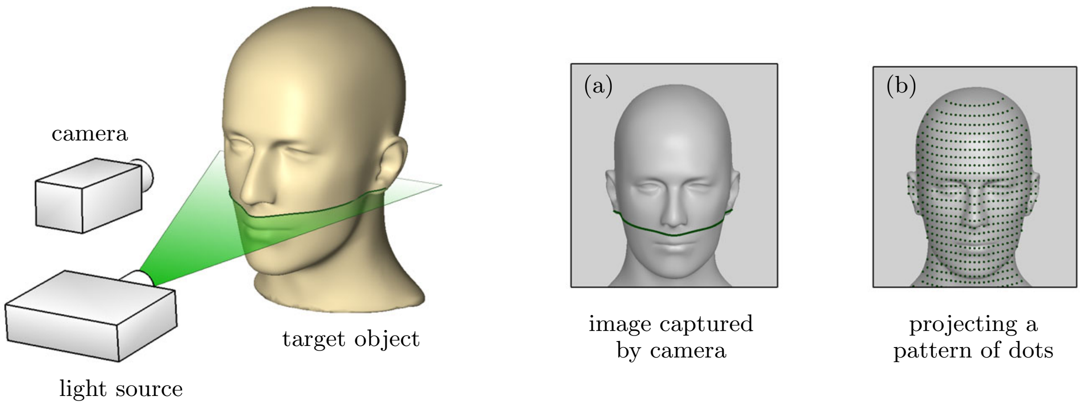




Structured light scanning



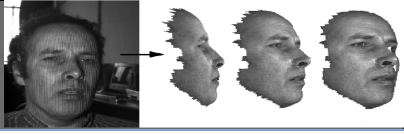


1. Operates by projecting a pattern of light onto the target surface

2. A camera records the pattern as it reflects from the surface

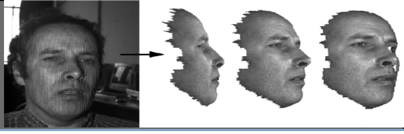
3. The shape of the captured pattern is combined with the spatial relationship between the light source and the camera, to determine the 3D position of the surface along the pattern

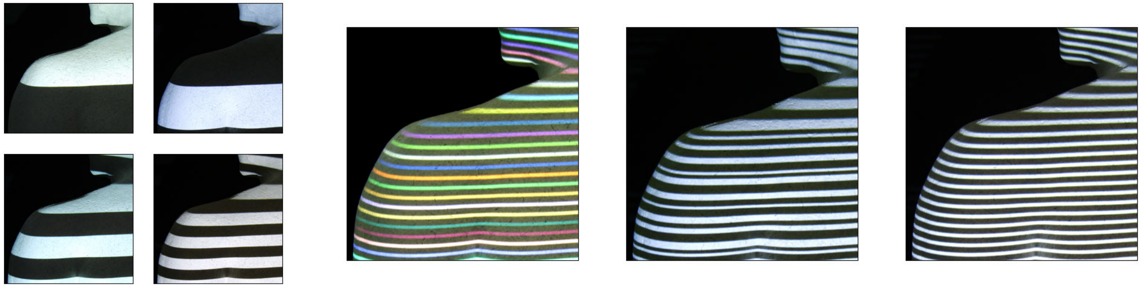
Important characteristics



- The cost of the system is fairly low as it requires only a light source, such as a slide or LCD projector, and a standard digital camera (for a visible spectrum solution).
- The speed of acquisition allows for rapid, almost instantaneous, acquisition.
- The accuracy of the system can be controlled by the projected pattern and camera resolution.
- The process can be made completely non-intrusive by implementing a near-infrared (NIR) emitter and an NIR sensitive sensor to capture the image.
- As with stereo vision, the system is constrained only by the combined field of view of the projector and camera, and their focus distances.

Coding schemes

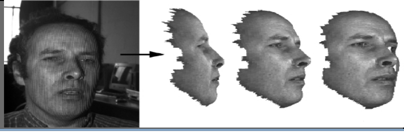




(a) time-multiplexing (b) colour coding (c) variable width (d) uncoded stripes

a) Time-multiplexing projects a series of luminance patterns over time so that every recorded point is encoded by a sequence of intensities. Only for motionless objects.
b) Colour coding stripes are used to differentiate between the recorded stripes. It can cause problems where the surface exhibits weak or ambiguous reflection properties.
c) Uneven distribution in stripe width reduces the resolution and can cause difficulties on a surface with variable depth.
d) Projecting uncoded stripes is the preferred method.

Advantages of uncoded stripes

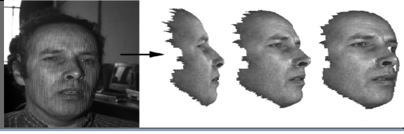


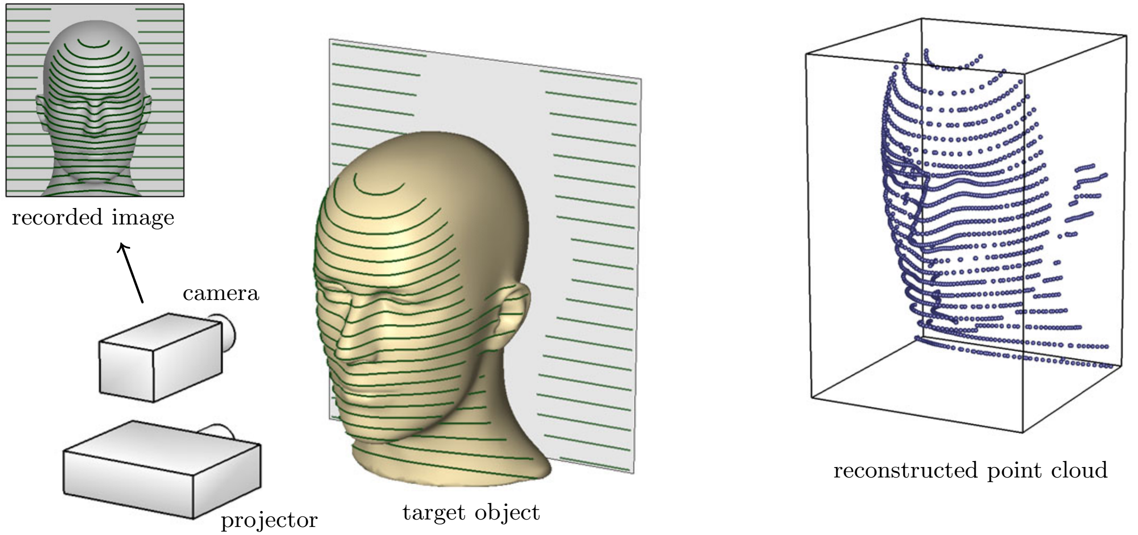
- It allows for “one-shot” scanning, such that the acquisition is nearly instantaneous and can be performed at frame rate (unlike time-multiplexing methods),

- the maximum resolution from a single scan can be achieved with a sufficiently dense pattern of stripes (unlike variable width coding), and

- it can be applied consistently to a variety of different object tones and colours (unlike a pattern of colour coded stripes).

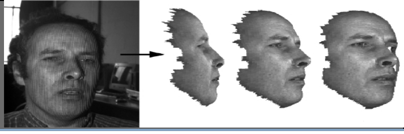
A scanner layout

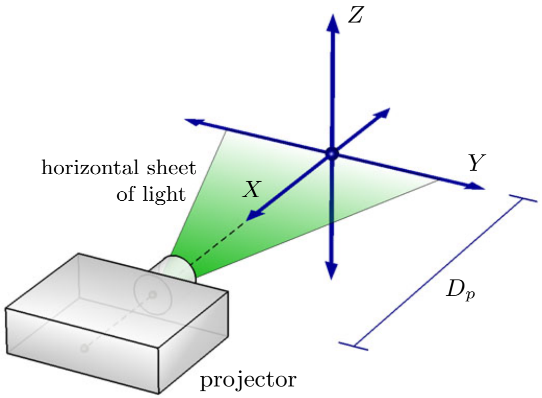




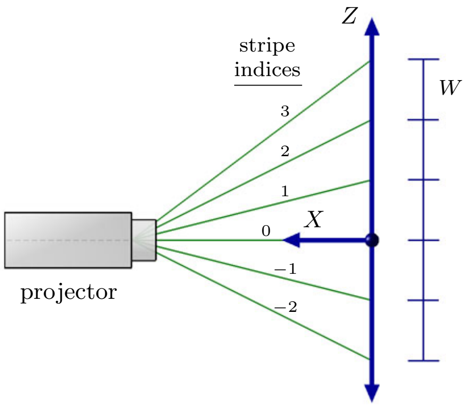
A series of parallel stripes is projected onto the surface of an object. A recorded image of this scene reveals the shape of the surface along those stripes, and can be used to reconstruct a 3D point cloud.

Defining the coordinate system





(a) defining the coordinate system

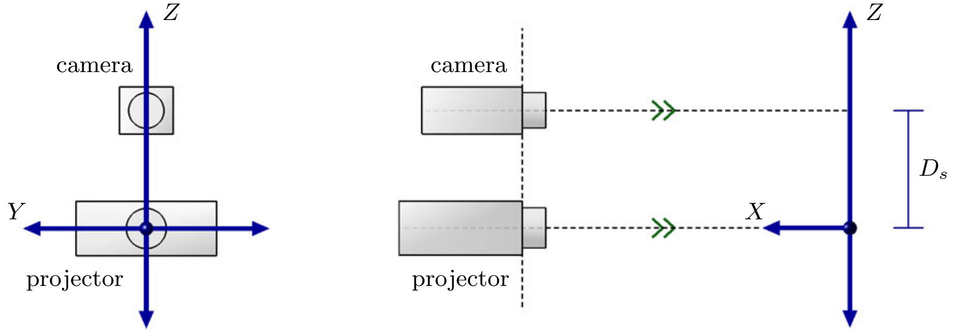


(b) assigning stripe indices

a) We define a coordinate system in relation to the projector.

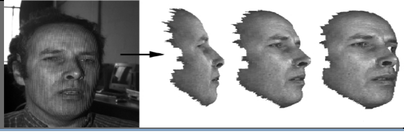
b) Indices are assigned to planes emanating from the projector. The planes project to evenly spaced stripes on the Y –Z plane.

The relationship between camera and projector



The camera is positioned at a distance Ds above the projector so that its central axis lies in the X–Z plane and is parallel to the projector axis.

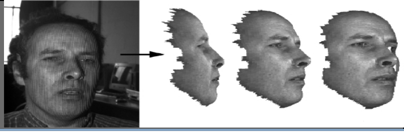
Mapping image points to surface points

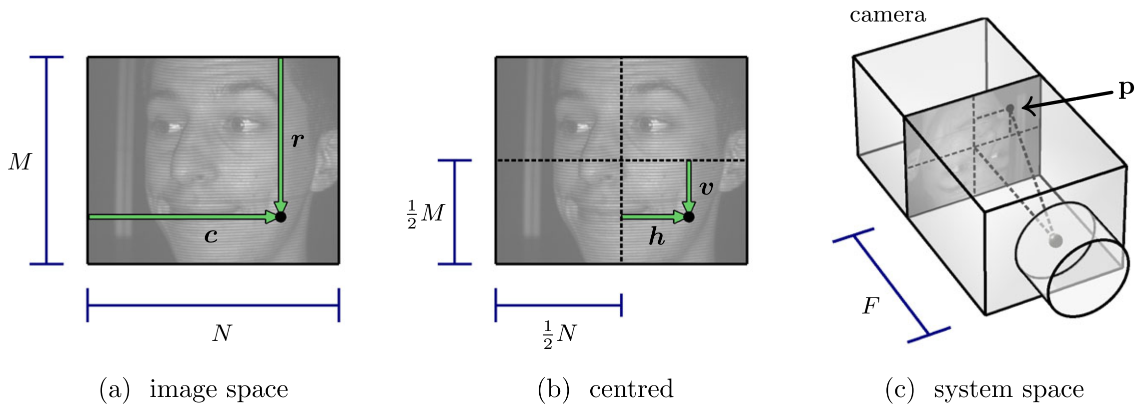


Three steps:

1. An image point (or pixel) is transformed to a point on the sensor plane of the camera in system space;
2. the effects of radial lens distortion are corrected for;
3. the intersection of the appropriate camera ray and the plane cast from the projector, corresponding to a specific stripe index, is found.

Image space to system space





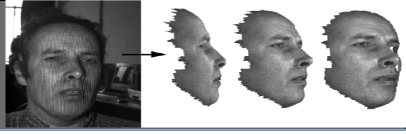
The position of a pixel in the image at row ***r*** and column ***c*** is transformed to coordinates (***v***,***h***) and then to a point ***p*** in system space.

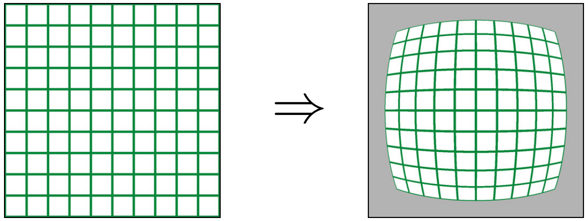
$$v = r - \tfrac{1}{2}(M+1) \quad \text{and} \quad h = c - \tfrac{1}{2}(N+1)$$

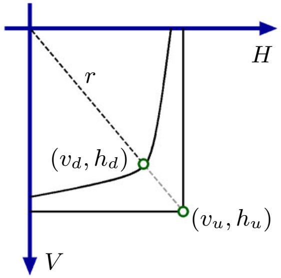
$$\mathbf{p} = \mathbf{c} + (0, -hPF, vPF)$$

Note that we express the pixel size specifically as *PF* so that *F* cancels in some of the equations that follow.

Radial distortion correction







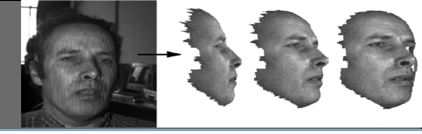
A recorded image can suffer from radial lens distortion, which can be corrected (in an estimated sense) by a transformation.

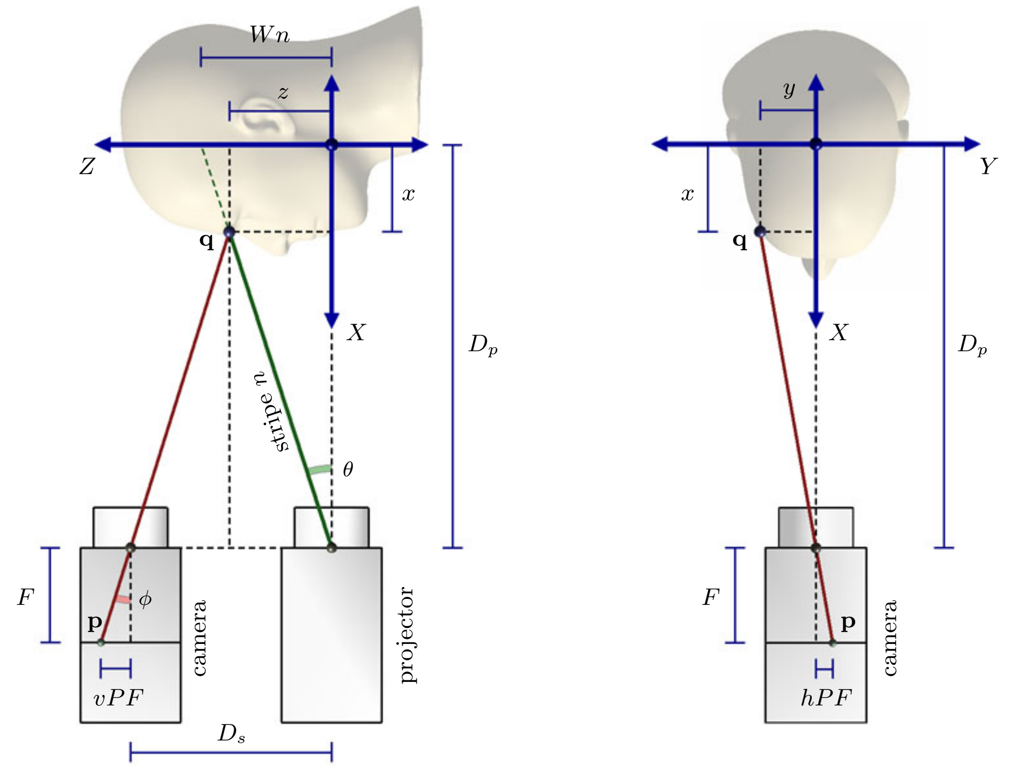
We use the Tsai camera model:

$$h_u = h_d(1 + kr^2), \qquad v_u = v_d(1 + kr^2), \qquad \text{with} \quad r = \sqrt{h_d^2 + v_d^2}.$$

k is the lens distortion coefficient which should be determined for a specific camera and lens prior to scanning.

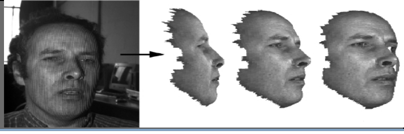
Mapping from (v, h, n) to (x, y, z)





The geometry of the scanner, as viewed down the Y -axis (left) and down the Z-axis (right), is used to map points in the image to corresponding surface points in system space

Mapping surface points



By triangulation:

$$\frac{z}{D_p - x} = \frac{Wn}{D_p} \quad \Longrightarrow \quad z = \frac{Wn}{D_p}\left(D_p - x\right)$$

$$\frac{vPF}{F} = \frac{D_s - z}{D_p - x} \quad \Longrightarrow \quad z = D_s - vP\left(D_p - x\right).$$

Note that by construction $D_p > x,\ D_p > 0 \text{ and } F > 0$

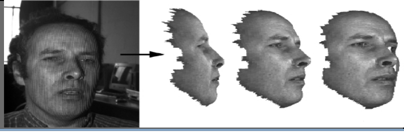
Combining these expressions:

$$\frac{Wn}{D_p}\left(D_p - x\right) = D_s - vP\left(D_p - x\right) \quad \Longrightarrow \quad x = D_p - \frac{D_p D_s}{vPD_p + Wn},$$

$$z = \frac{Wn}{D_p}\left(D_p - D_p + \frac{D_p D_s}{vPD_p + Wn}\right) = \frac{WnD_s}{vPD_p + Wn}$$

$$\frac{y}{D_p - x} = \frac{hPF}{F} \quad \Longrightarrow \quad y = hP(D_p - x) \; = \; \frac{hPD_pD_s}{vPD_p + Wn}.$$

Choosing system parameter values



Dp: the distance between the projector and the system origin

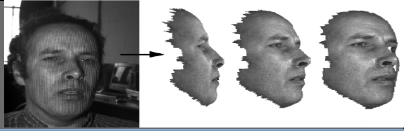
W: the width between successive stripes on the calibration plane

Ds: the distance between the camera and the projector

P: the pixel size on the sensor plane of the camera

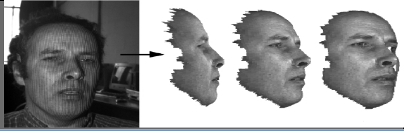
k: the radial lens distortion coefficient

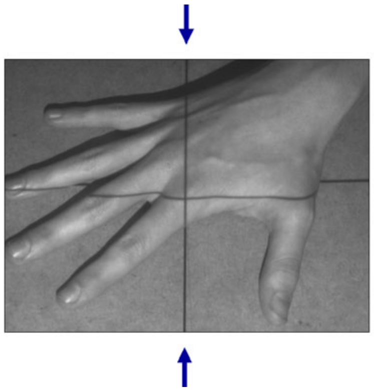
Fixing system variables

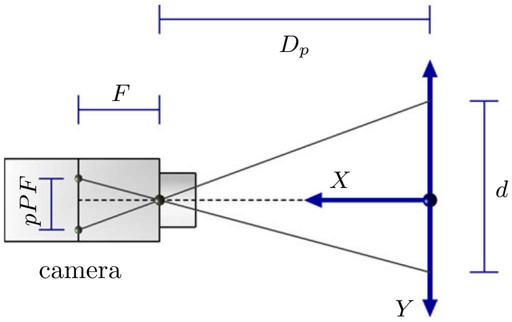


1. Choose a calibration plane:
    1. This plane will coincide with the Y –Z plane in system space and the scanner will be positioned and calibrated in relation to it.
2. Calibrate the projector [Dp, W, centre stripe]:
    1. The projector is positioned in front of the calibration plane such that its central axis is normal to that plane. The parameter Dp can then be measured directly as the perpendicular distance between the focal point of the projector and the calibration plane.
    2. The parameter W is measured as the spacing between two consecutive stripes on the calibration plane. Greater accuracy can be achieved by measuring a width $W*$ over m stripes, and calculating $W = W*/m$.
    3. It is also necessary to identify and mark one reference stripe of a known index, so that the other stripes in the image can be assigned indices relative to it. To accomplish this we can first locate the centre stripe with index 0 (zero).

Fixing system variables



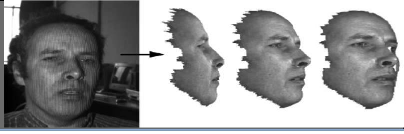


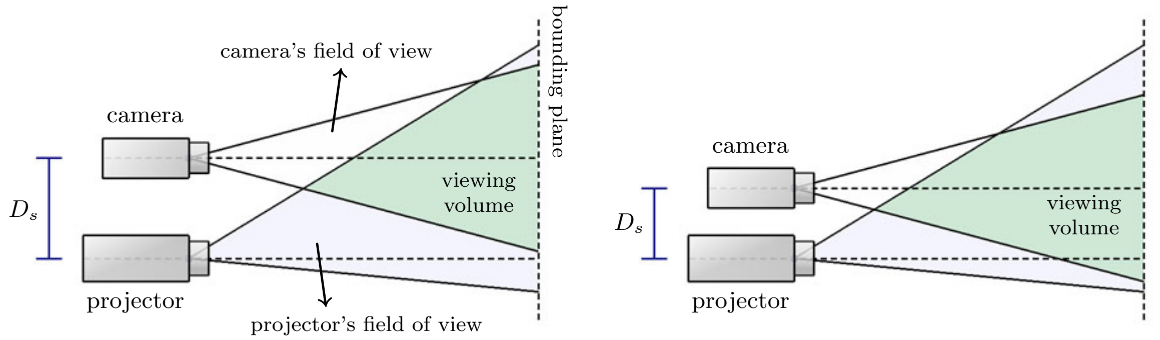


3. Calibrate the camera [P]: a horizontal distance d is marked on the calibration plane and recorded by the camera. The number of pixels, p, between the endpoints of d is determined. Then by triangulation:

$$\frac{pPF}{F} = \frac{d}{D_p} \quad \Longrightarrow \quad P = \frac{d}{pD_p}.$$

Viewing volume

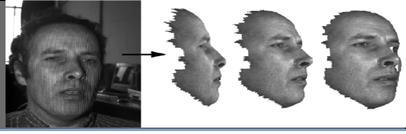


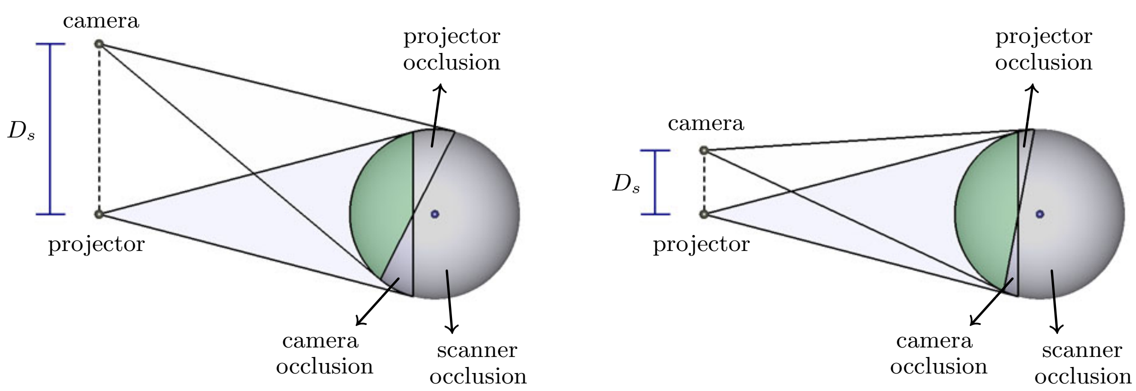


The viewing volume of the scanner is the space visible by both the camera and the projector. This volume is likely to increase as Ds is decreased.

Thus, Ds should be fixed as small as possible, i.e. have the camera as close to the projector as possible, because it may (1) increase the viewing volume and (2) decrease the likelihood of occlusions.

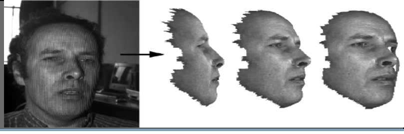
Occlusions

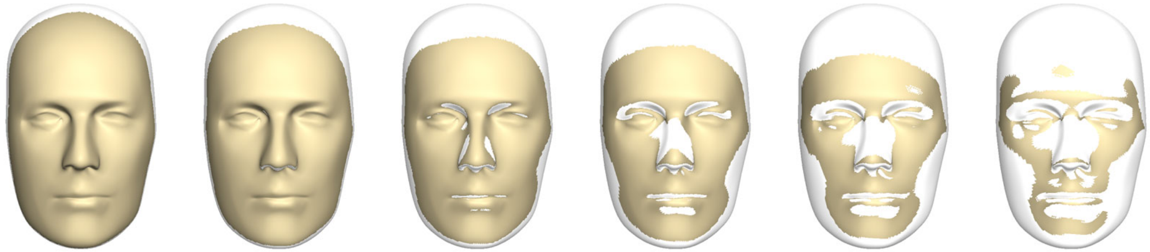




- camera occlusion : a region visible from the projector but not from the camera;
- projector occlusion : a region visible from the camera but not from the projector;
- scanner occlusion: a region not visible from either the projector or the camera.

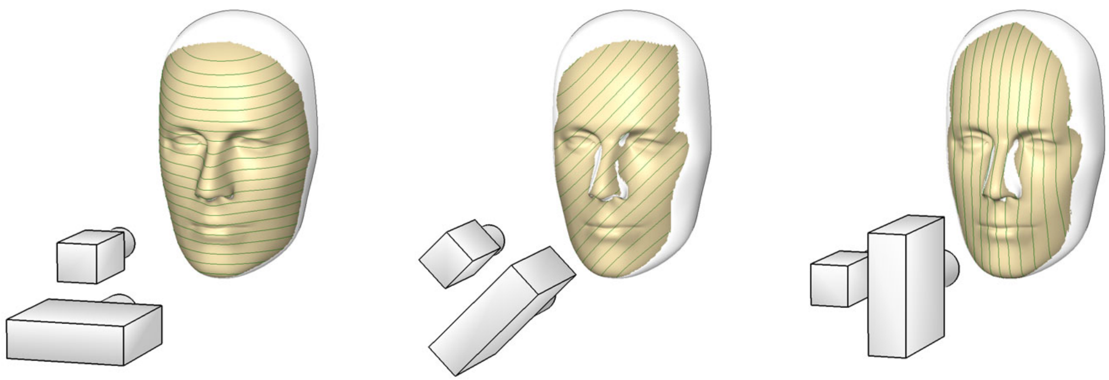
Occlusions and angle of projection





$D_s = 50$ $D_s = 100$ $D_s = 250$ $D_s = 400$ $D_s = 600$ $D_s = 1,000$

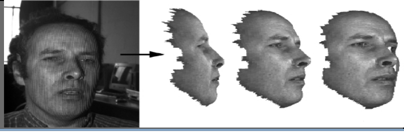
- Scan area is decreased as Ds is increased

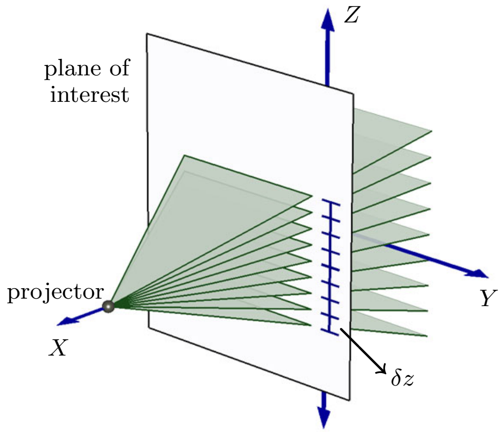


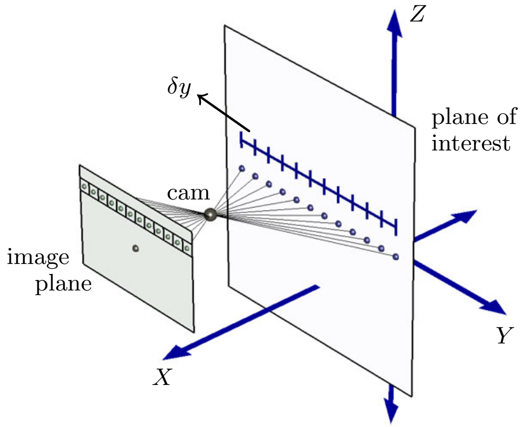
(a) horizontal stripes (b) diagonal stripes (c) vertical stripes

- Size of scan region may also depend on angle of projection

Resolution







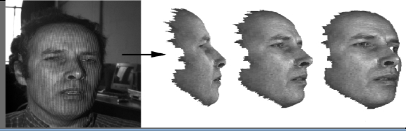
- The vertical resolution (left) of the scanner is affected by the spacing of the projected stripes. The horizontal resolution (right) is dependent on the horizontal dimension of the pixel space.

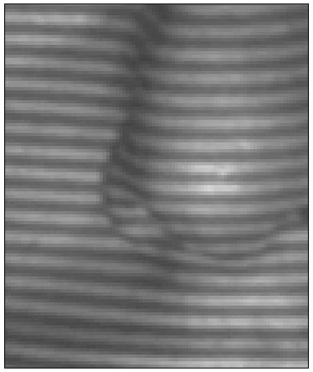
$$\delta z = \frac{W}{D_p}(D_p - x)$$

$$\delta y = P(D_p - x)$$

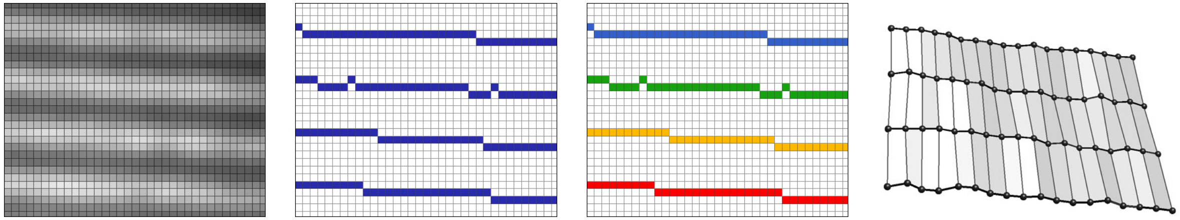
$$\begin{aligned} \delta x &= \frac{D_p D_s}{vPD_p + Wn} - \frac{D_p D_s}{(v+1)PD_p + Wn} \\ &= \frac{PD_p^2 D_s}{[vPD_p + Wn][(v+1)PD_p + Wn]}. \end{aligned}$$

Building 3D models





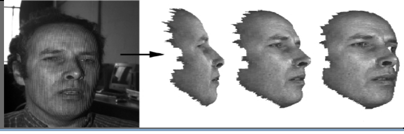
- The image contains a darker stripe which is the centre of the system

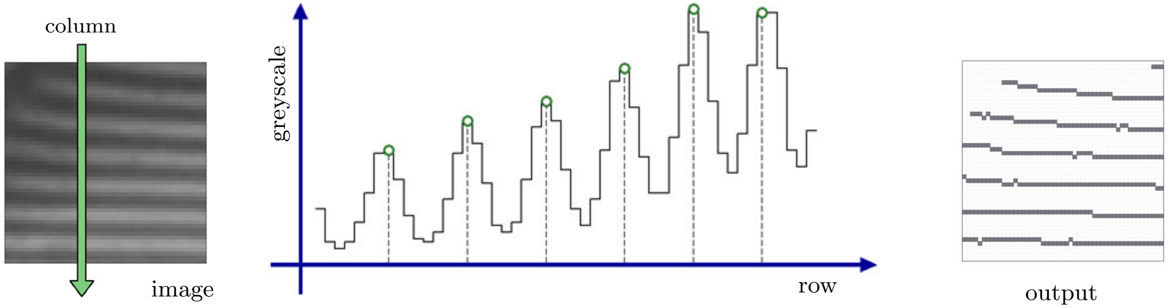


captured image (1) locate stripe pixels (2) index stripes (3) map to 3D space

- Steps to 3D reconstruction: locate stripes, index stripes, map to 3D space.

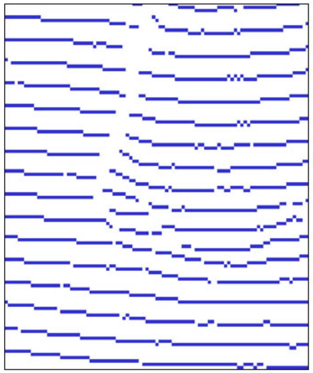
Locating stripes

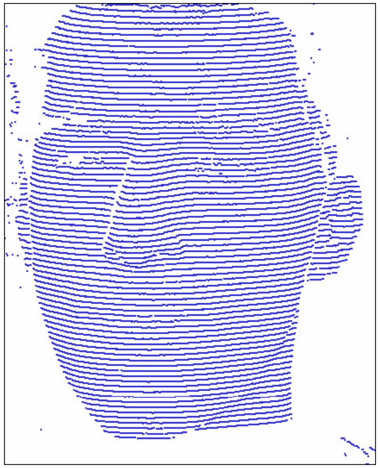




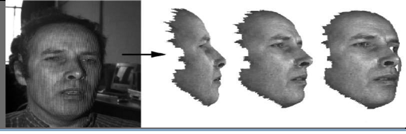
- Stripe pixels are determined as local maxima in the greyscale values of every column in the image:

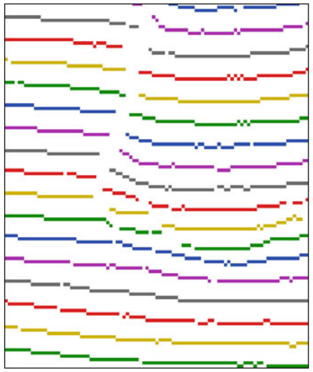
$$A(r,c) > A(r-1,c) \quad \text{and} \quad A(r,c) > A(r+1,c).$$

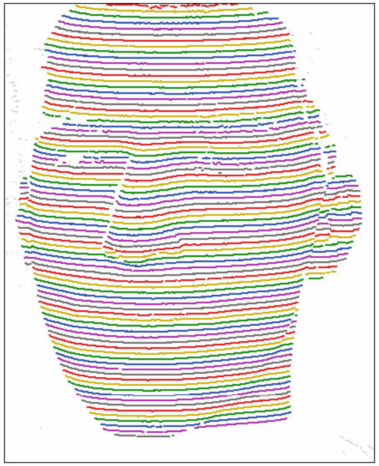




Indexing the stripes

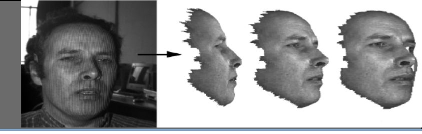




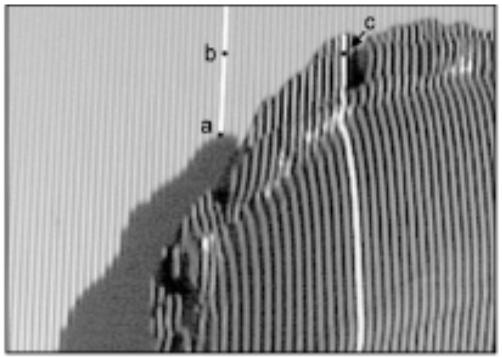


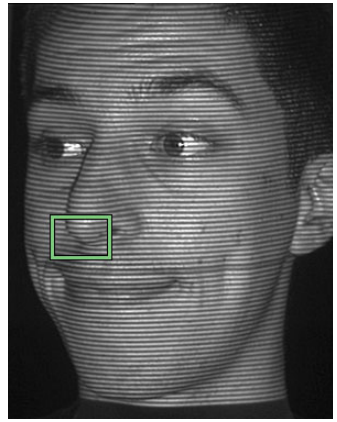
- Starting from the centre stripe, different indices are depicted as alternating colours in a repeating sequence
- A number of algorithms have been implemented based on flood filling (Robinson), MST-Maximum Spanning Tree (Brink)
- This is a problem that can be improved

Undetectable index shifts

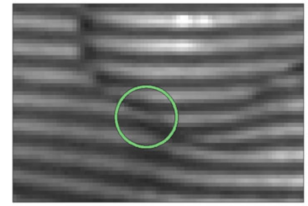


Sudden drop in surface depth



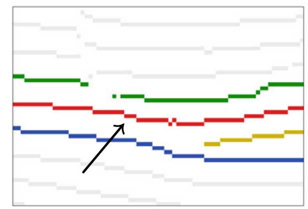


(a) captured image

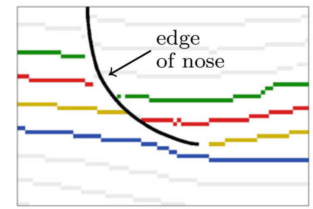


(b) close-up

(c) stripe pixels

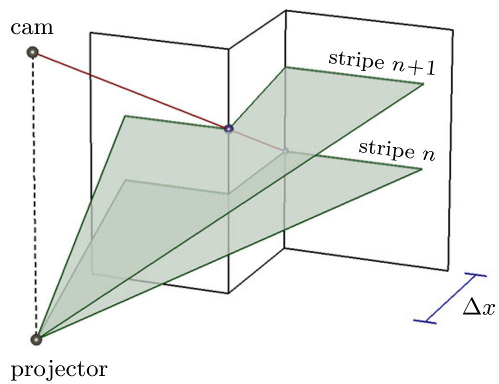


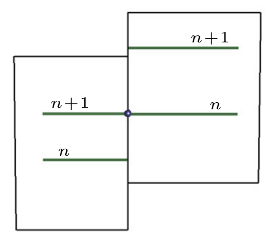
(d) incorrect indexing



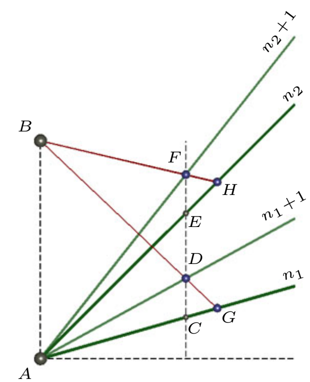
(e) correct indexing

Critical depth changes

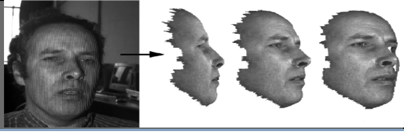


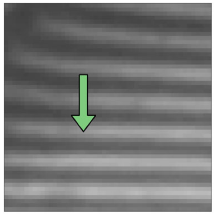


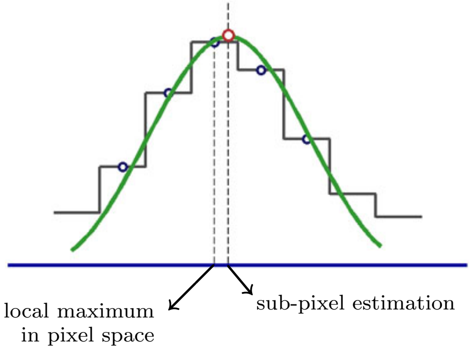
view from the camera



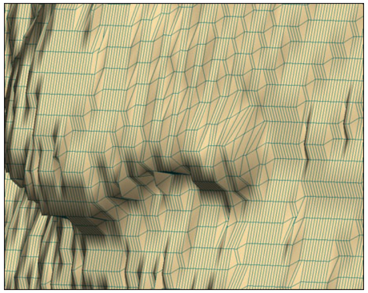
Sub-pixel estimation

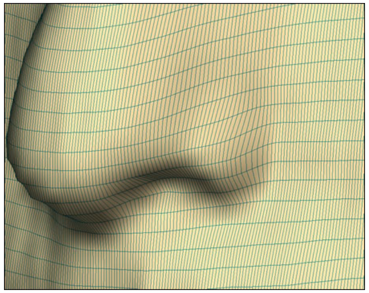






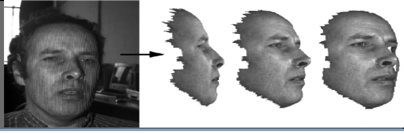
- A Gaussian profile is fitted to a neighbourhood of a located stripe pixel in the image.

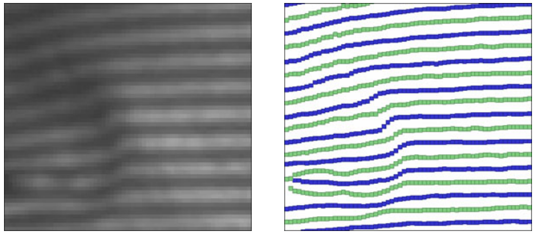




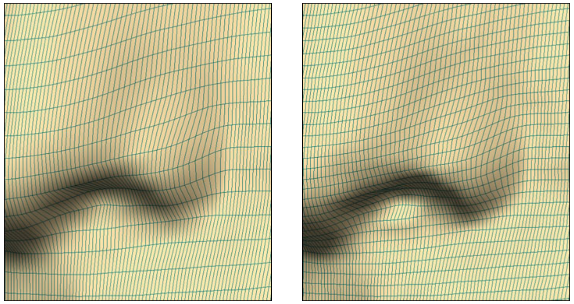
- Left without sub-pixel estimation, right with spe

Incorporating white and black stripes





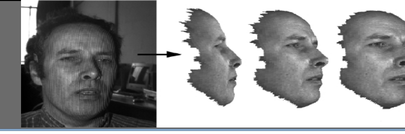
(a) black stripes located between white ones

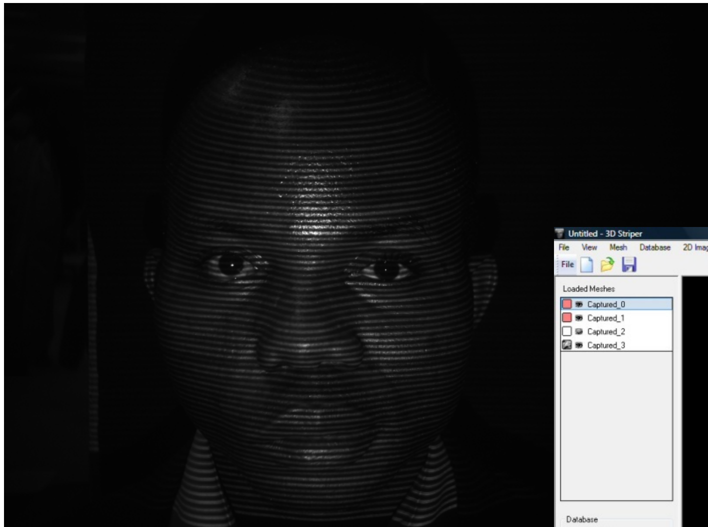


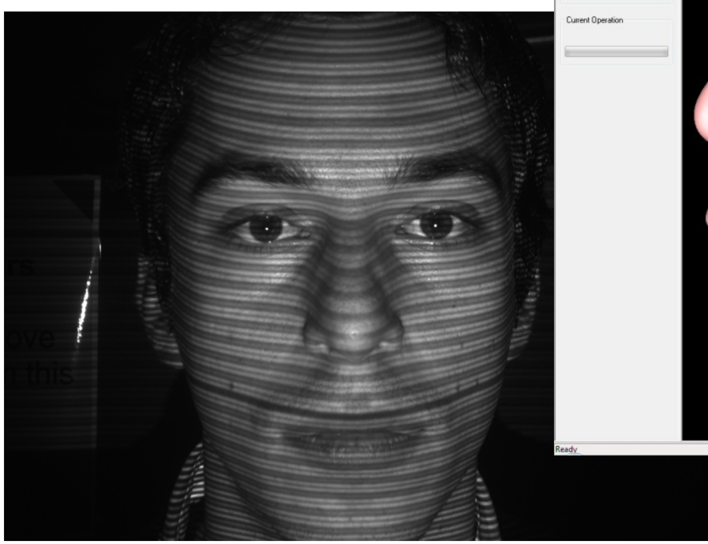
(b) result on the reconstructed surface

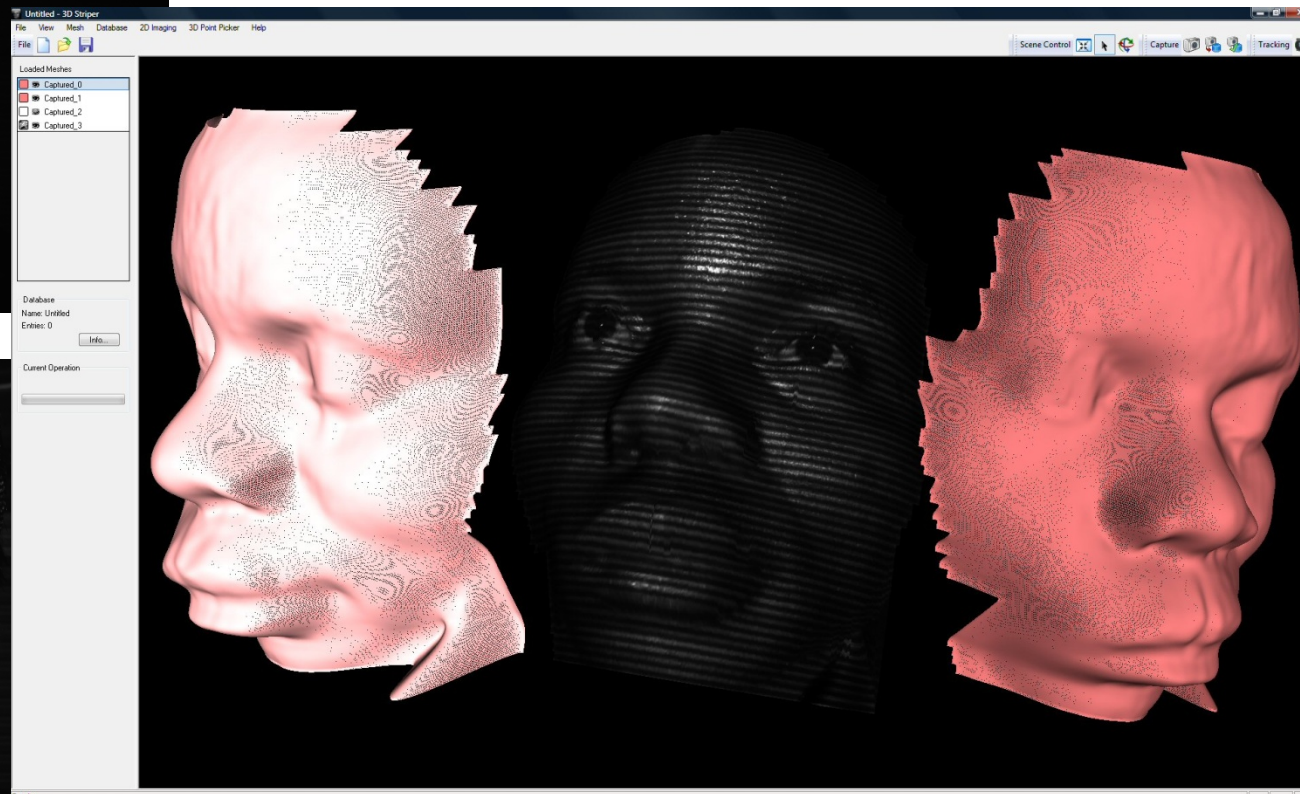
- A simple technique to double the resolution in the direction across the stripes is to incorporate the valleys or dark stripes. The effects are illustrated above.
- However detecting valleys is less reliable than detecting peaks. This is an are that needs improved algorithms.

Robustness to illumination

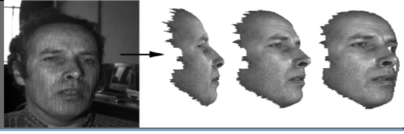


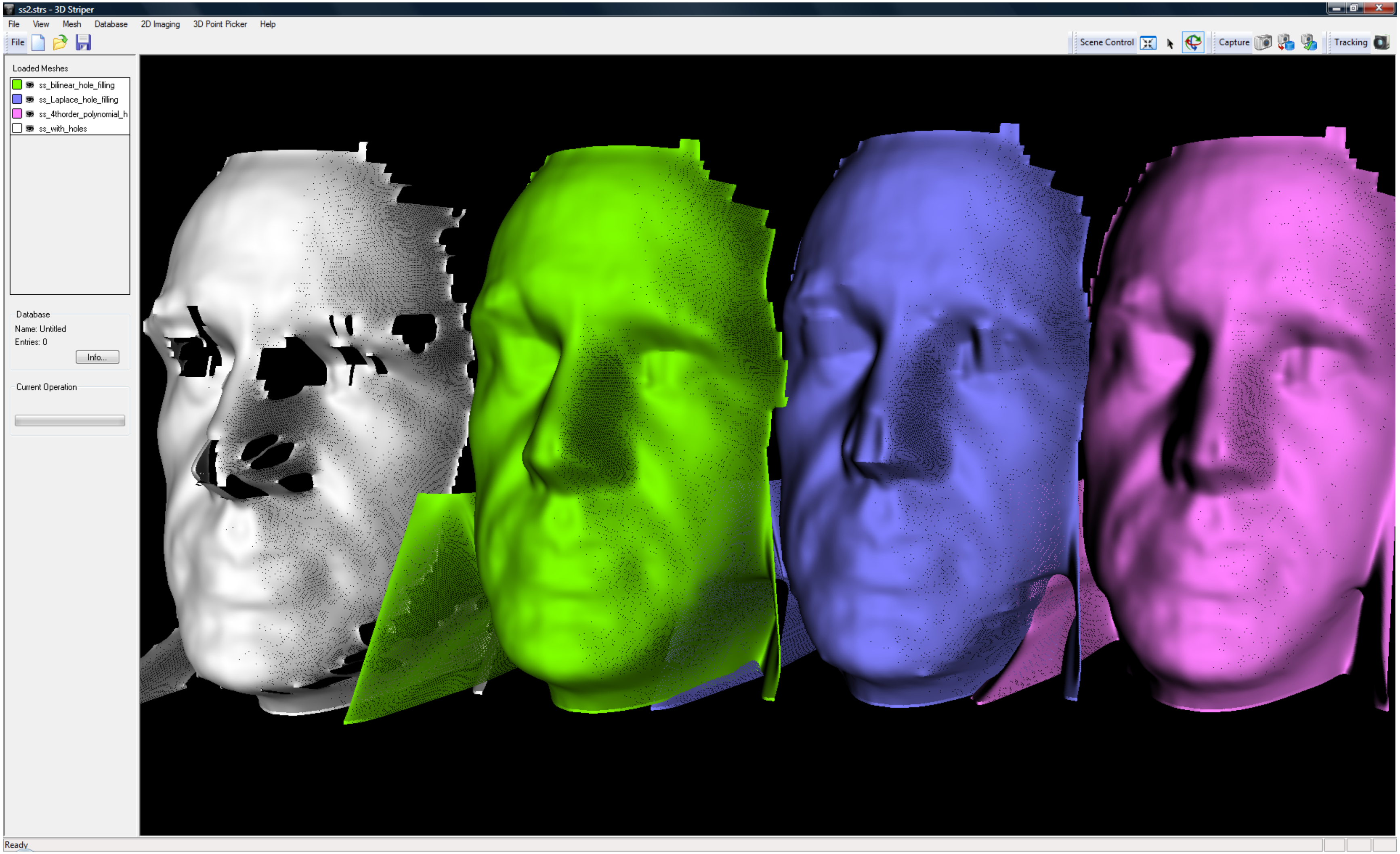




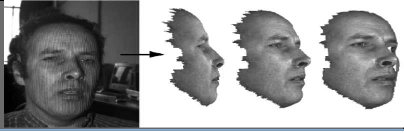


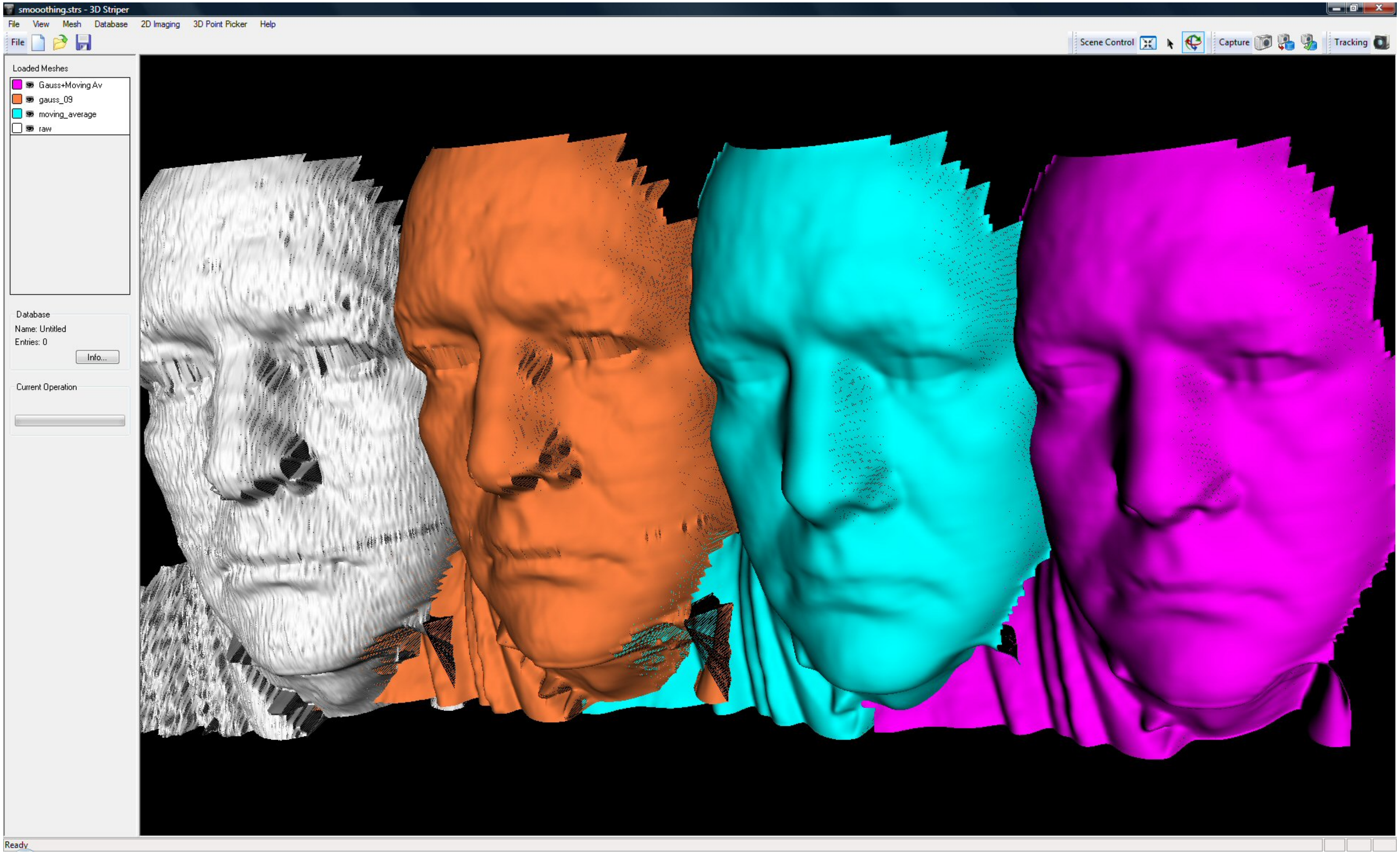
3D post-processing: hole filling



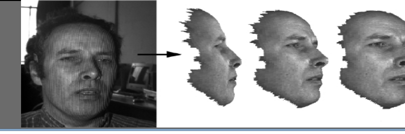


3D post-processing: smoothing

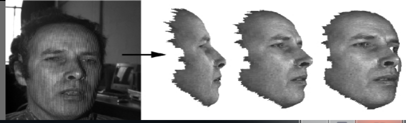


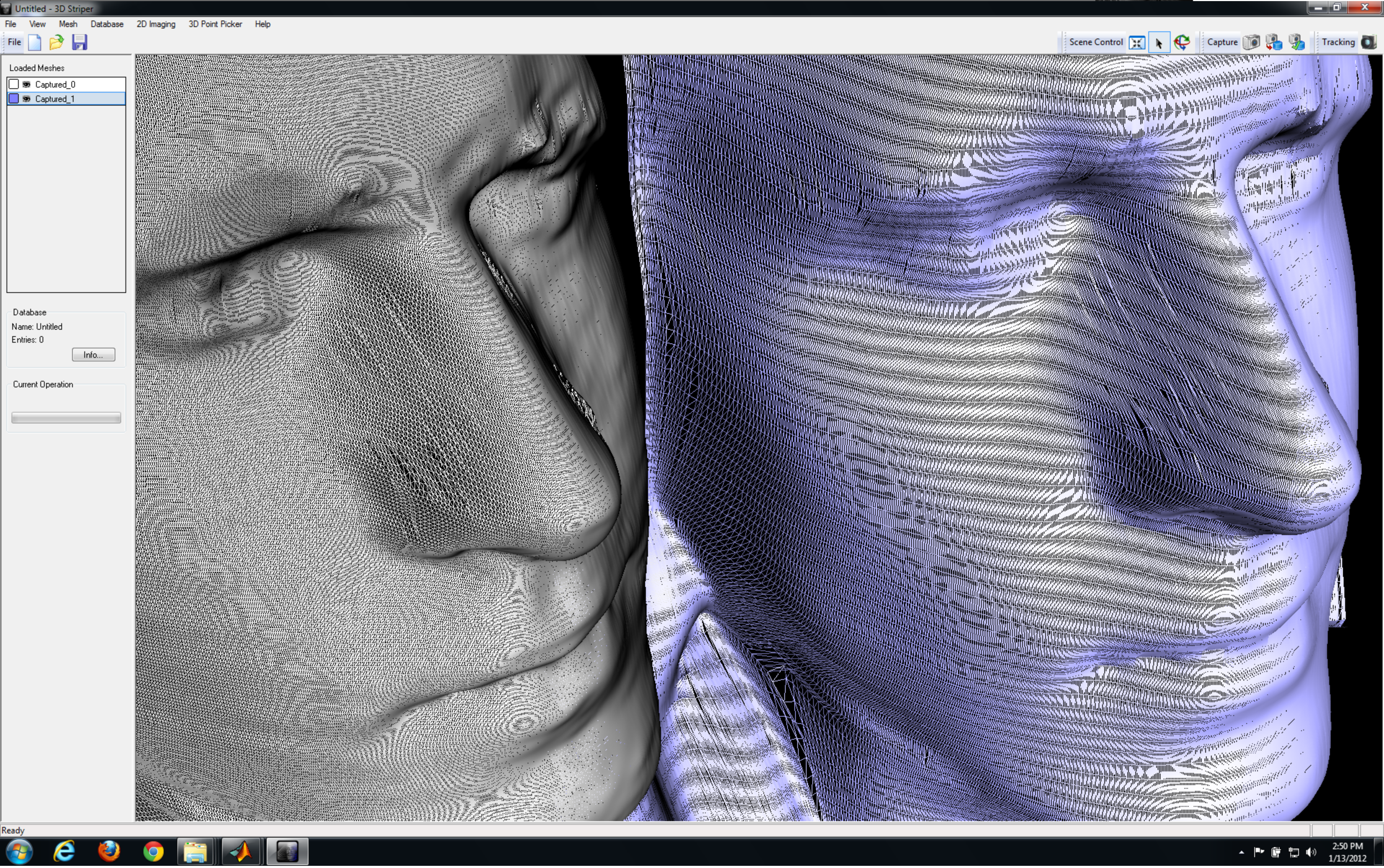


3D post-processing: noise removal

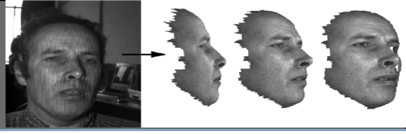


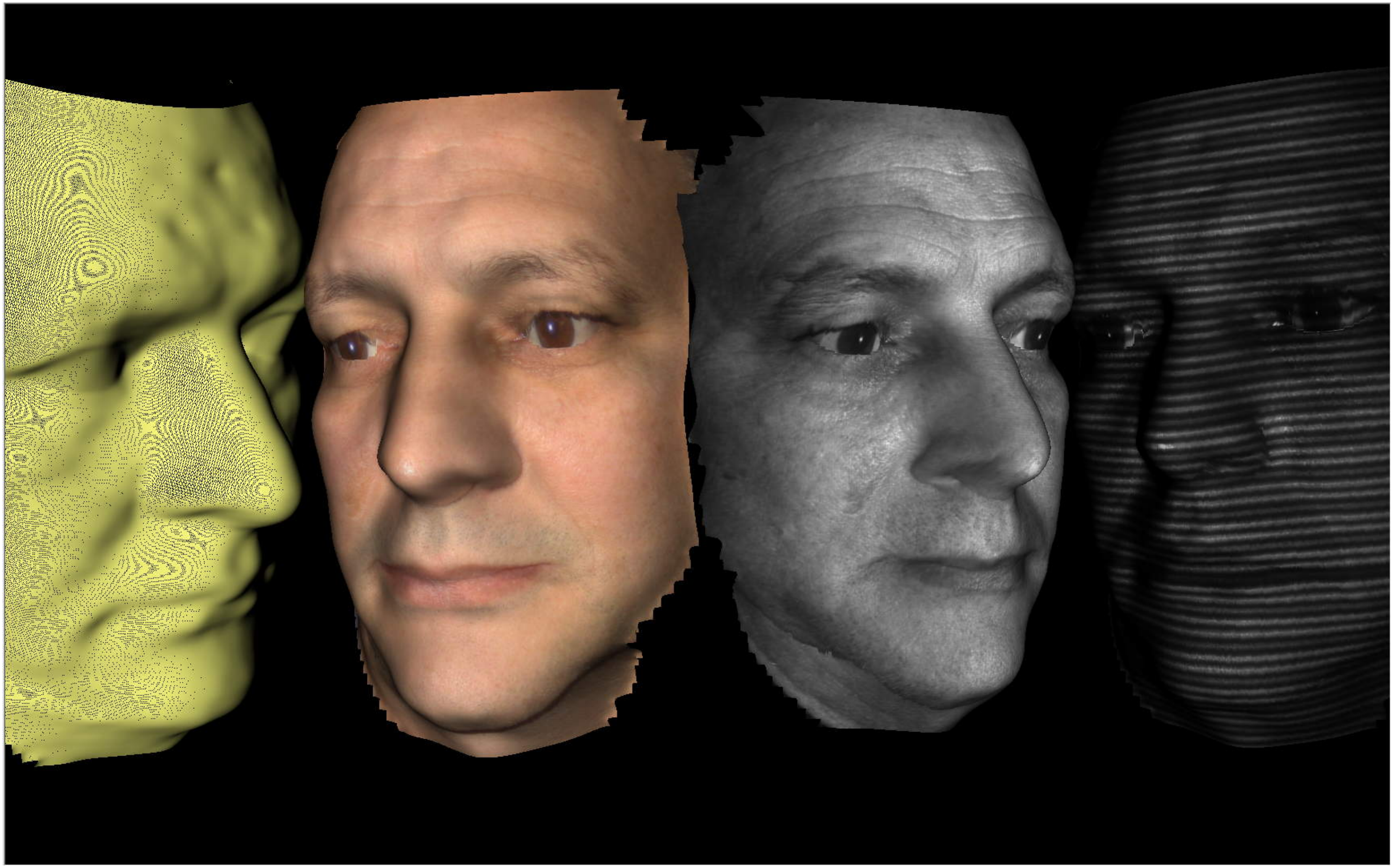
3d post-processing: mesh subdivision



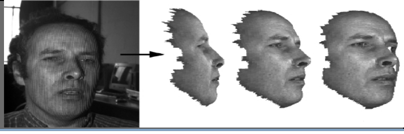


Texture mapping



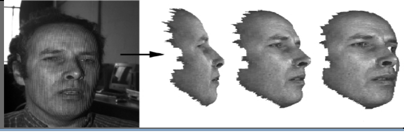


Conclusions



- Simple and inexpensive construction of 3D scanner
- Fast, can operate in real-time
- 3D reconstruction in 40 ms
- The full cycle from acquisition, 2D image processing, 3D reconstruction, 3D post-processing takes 230 ms
- 3D video at ~5 frames per second, possibility to overlay in real time with an augmented reality system
- Near infrared camera and projector is the way forward as it generates its own light and is independent of ambient illumination
- Possibility of miniaturization medical imaging
- A number of computing and engineering challenges remain

Contact details



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Acknowledgments

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