Development and accuracy evaluation of Coded phase-shift 3D scanner

Pranav Kant Gaur,D.M.Sarode,S.K.Bose

Graphics and Visualization Section
Computer Division
Bhabha Atomic Research Centre

pranav@barc.gov.in

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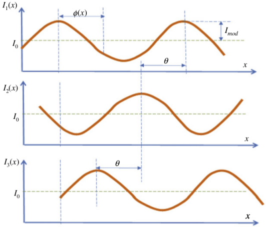
Agenda

Introduction

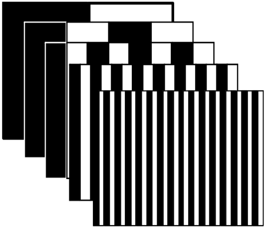
1. What?
    1. 3D scanner
        1. Digital reconstruction of real world scene.
2. Why?
    1. Applications
        1. Medical: Dental model reconstruction for teeth implantation
        2. Scientific analysis: Study of dynamics for example, C.F.D, machine component dynamics etc.
        3. Biometric security: 3D face authentication, thumb pattern authentication
        4. Entertainment : XBOX Kinect etc.
3. How?
    1. Key problems
        1. Stereo correspondence: At least 2 views required
        2. System calibration: Mapping measurement units of optical elements to physical units(mm,feet etc.)
        3. Triangulation: Compute 3D coordinates given system calibration and stereo correspondence

Approach used

1. Stereo correspondence:
   1. Coded phase shift approach



(a) Phase shift approach



(b) Binary coded approach

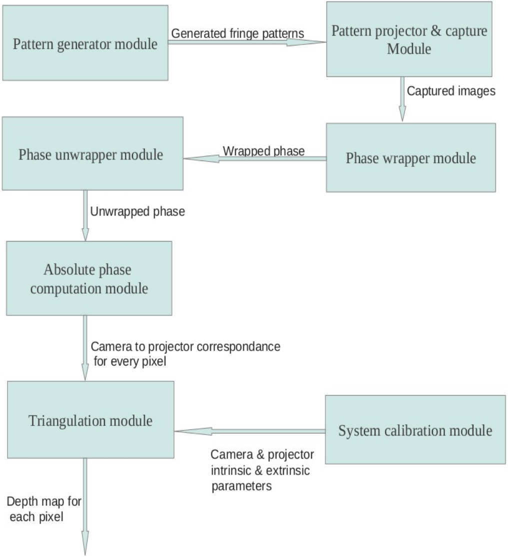
Figure: Solving stereo correspondence

1. System calibration
   1. OpenCV camera calibration and VPCLib projector calibration algorithm used.

1. Triangulation
   1. Camera and projector model equations are solved for corresponding camera and projector pixels.

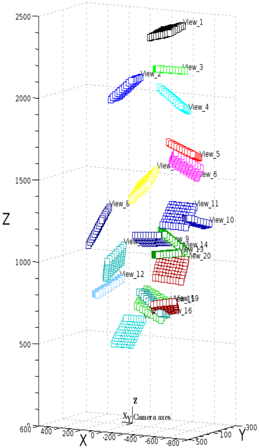
3D scanner system:Overview

(a) System setup

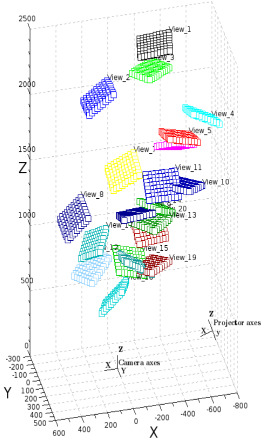


(b) Software architecture

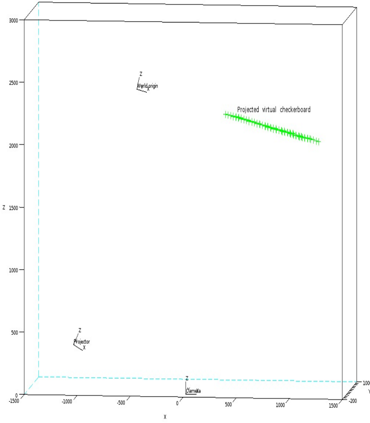
System calibration



(a) Camera calibration



(b) Projector calibration



(c) Extrinsic calibration

Pattern generation

Model for phase shifted sinusoidal patterns:

$$
\begin{aligned}
P_1^v &= A_v + B_v * cos(\theta_v - \alpha) \\
P_2^v &= A_v + B_v * cos(\theta_v) \\
P_3^v &= A_v + B_v * cos(\theta_v + \alpha)
\end{aligned}
\tag{1}
$$

where $\theta_v = 2\pi \frac{x}{fringe\ \ width}$

Model for binary coded patterns:

$$N_v^{codes} = \frac{W_{projector}}{w_{fringe}} \tag{2}$$

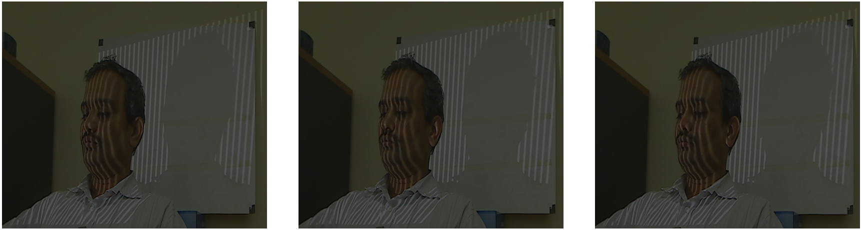
$$N_v^{patterns} = \log_2(N_v^{codes}) \tag{3}$$

$$Intensity_{(i,j)} = \lfloor i/(w_{fringe} * 2^{pattern\ \ number}) \rfloor \tag{4}$$

(d) (e) (f) (g) (h) (i)

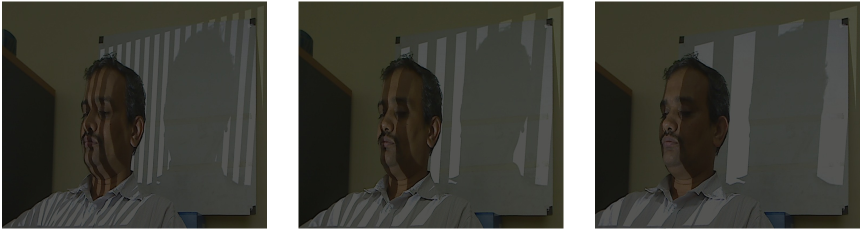
Figure: Vertical phase-shifted patterns & binary coded patterns

Pattern projection and capture



(a) (b) (c)

Figure: Captured vertical phase-shifted patterns



(a) (b) (c)

Figure: Captured binary coded patterns

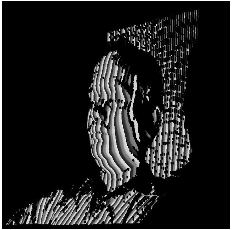
Phase wrapping

Assumed illumination model for 3 phase shifted pattern approach:

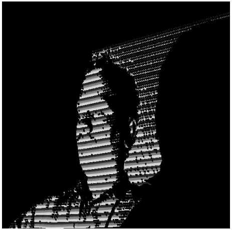
$$\begin{aligned} I_1^{v/h} &= I_{dc}^{v/h} + I_{mod}^{v/h} * cos(\theta_{v/h} - \alpha) \\ I_2^{v/h} &= I_{dc}^{v/h} + I_{mod}^{v/h} * cos(\theta_{v/h}) \\ I_3^{v/h} &= I_{dc}^{v/h} + I_{mod}^{v/h} * cos(\theta_{v/h} + \alpha) \end{aligned} \tag{5}$$

Hence,

$$\begin{aligned} \theta_v &= tan^{-1}\left[\frac{\sqrt[2]{3}(I_1^v - I_3^v)}{2I_2^v - I_1^v - I_3^v}\right], -\pi \leq \theta_v \leq \pi, \\ \theta_h &= tan^{-1}\left[\frac{\sqrt[2]{3}(I_1^h - I_3^h)}{2I_2^h - I_1^h - I_3^h}\right], -\pi \leq \theta_h \leq \pi \end{aligned} \tag{6}$$



(a) Vertical wrapped phase



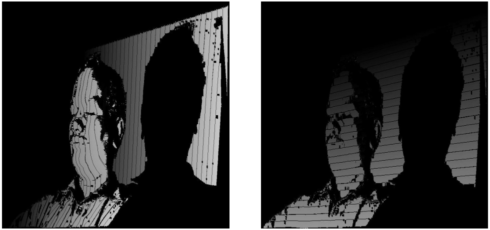
(b) Horizontal wrapped phase

Phase unwrapping module

Unwrapped phase (ψ_v, ψ_h) maps (θ_v, θ_h) to its correct 2π multiple:

$$\begin{aligned} \psi_v &= \theta_v + 2\pi * C_v \\ \psi_h &= \theta_h + 2\pi * C_h \end{aligned} \tag{7}$$

where,
$C_v(x, y)$: Decoded vertical binary code(or *vertical period number*) at any pixel (x,y).
$C_h(x, y)$: Decoded horizontal binary code(or *horizontal period number*) at any pixel (x,y).



(a) Vertical unwrapped phase

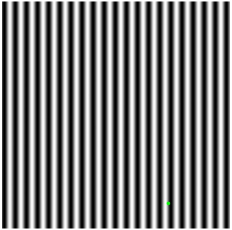
(b) Horizontal unwrapped phase

Figure: Computed unwrapped phase

Computing projector coordinates (X_p, Y_p) corresponding to a camera coordinates (X_c, Y_c)

$$X_p = \lfloor w_{fringe} * (\frac{\psi_v}{2\pi}) \rfloor, \quad Y_p = \lfloor w_{fringe} * (\frac{\psi_h}{2\pi}) \rfloor \tag{8}$$

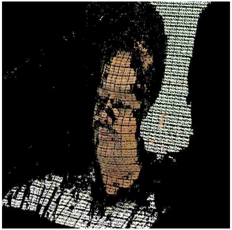
(a) Camera image



(b) Projector image

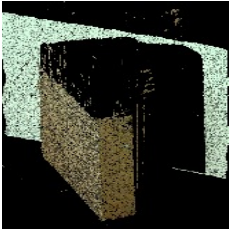
Figure: Stereo correspondence between camera and projector

(a) 2D face image



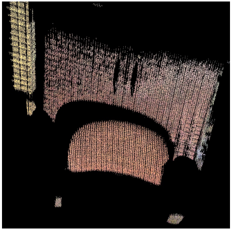
(b) 3D reconstruction of face

(c) 2D image of box in front of wall



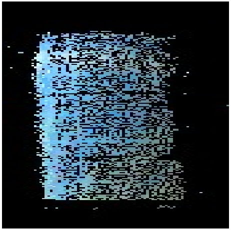
(d) 3D reconstruction of box in front of wall

(e) 2D image of a chair with background



(f) 3D reconstruction of chair with background

(g) A cup



(h) 3D reconstruction of cup

Figure: Some 3D reconstruction results

We followed,

$$Accuracy = \frac{\sum_{p=1}^{vp}\left[\frac{\sum_{i=1}^{vs_p}\left[\left(\frac{|True_p - measured_i|}{True_p}\right)*100\right]}{vs_p}\right]}{vp} \tag{9}$$

$$Precision = \frac{\sum_{p=1}^{vp}\left[\frac{\sum_{i=1}^{vs_p}\left[\left(\frac{|mean_p - measured_i|}{mean_p}\right)*100\right]}{vs_p}\right]}{vp} \tag{10}$$

1. A checkerboard target was scanned 10 times at a distance of $\sim$ 2.2m from camera projector system.
2. 6 individual lengths were measured using 3D data from scanner and compared against true values.
3. So, for our experiments we set N=10,vp=6.

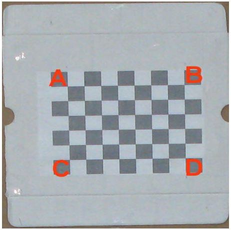


Figure: Measurement object

Length AB,BC,CD,AD,AC,BD were measured from 10 repetitions of 3D scans of object.

Table: Measurement accuracy and precision of developed coded phase-shift 3D-scanner

Metric	Value(in %)
Measurement accuracy	0.61
Precision	0.29

Conclusions

1. Combination of binary coded and phase shift algorithm provides more 3D resolution than simple binary codes and higher noise resilience than phase shifted approach.
2. Experimental system with measurement accuracy and precision within 1% at distance of ~ 2.2m from system.

Questions?