FOVEA

Foveated Vergent Active Stereo System

for

Dynamic Three-Dimensional Scene Recovery

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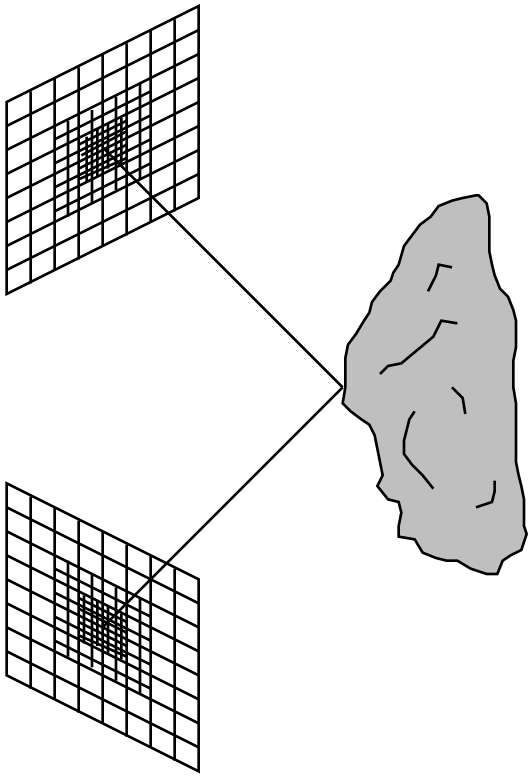
WHAT FOVEA DOES

GOAL: **Direct** the **attention** of **an active camera platform** to object surfaces and **recover 3-D** scene structure using **multiple fixations**

RESULT: **FO**veated **VE**rgent **A**ctive stereo system

FOVEA



METHOD

What composes **FOVEA** ?

- **Active** camera control
- Initial **Depth Recovery** ("bootstrapping")
- **Foveated** Vergent Stereo
- **Fixation** (where to look next)
- **Multi-Fixation** Dynamic **Data Accumulation**

MOTIVATION

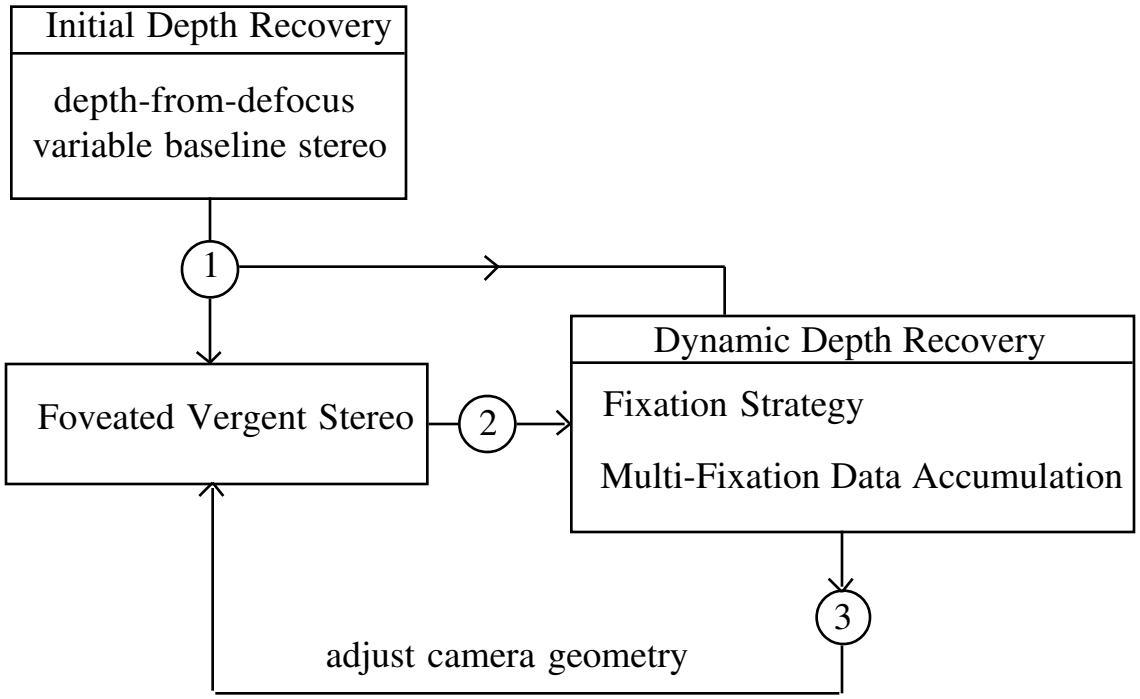
- Why is **FOVEA** useful?

  1. Tasks: 3-D mapping
     surface analysis
     navigation / hazard avoidance
     object recognition
  2. Better **constrain depth recovery** process
  3. **Aligned view** of 3-D region of interest
  4. **Integrate** information over **multiple fixations**
  5. Better **depth resolution**
  6. **Efficient** use of data via **foveal coding**

- What makes this problem challenging?

  1. Accurate camera fixation
  2. **Vergent stereo** correspondence
  3. Fixation strategy
  4. Data accumulation over **multiple fixations**

FOVEA Block Diagram



1 initial coarse depth map

2 foveated vergence depth map

3 accumulated depth map

OUTLINE

I. INITIAL DEPTH RECOVERY

II. FOVEATED VERGENT STEREO

III. DYNAMIC DEPTH RECOVERY

IV. CONCLUSION

INITIAL DEPTH RECOVERY IN FOVEA

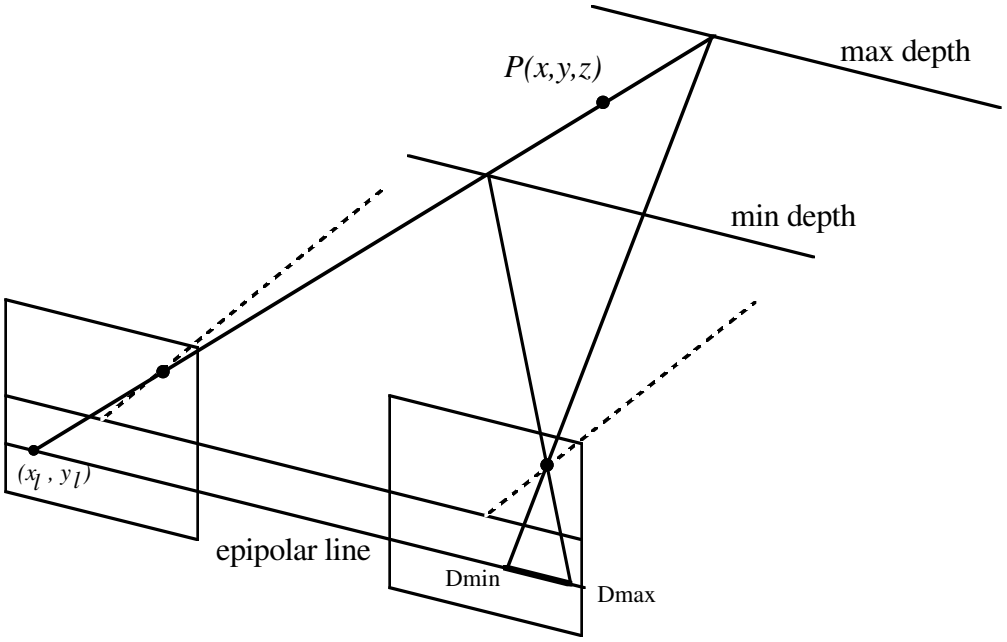
OBJECTIVES:

1. **Make vergent fixation possible**
2. **Adapt** to current scene structure

NEW TECHNIQUE -- Integrated IDR process:

1. **Adaptive Variable Baseline Stereo** (discussed here)
2. Maximum-Likelihood Depth-from-Defocus

PARALLEL BASELINE STEREO CORRESPONDENCE



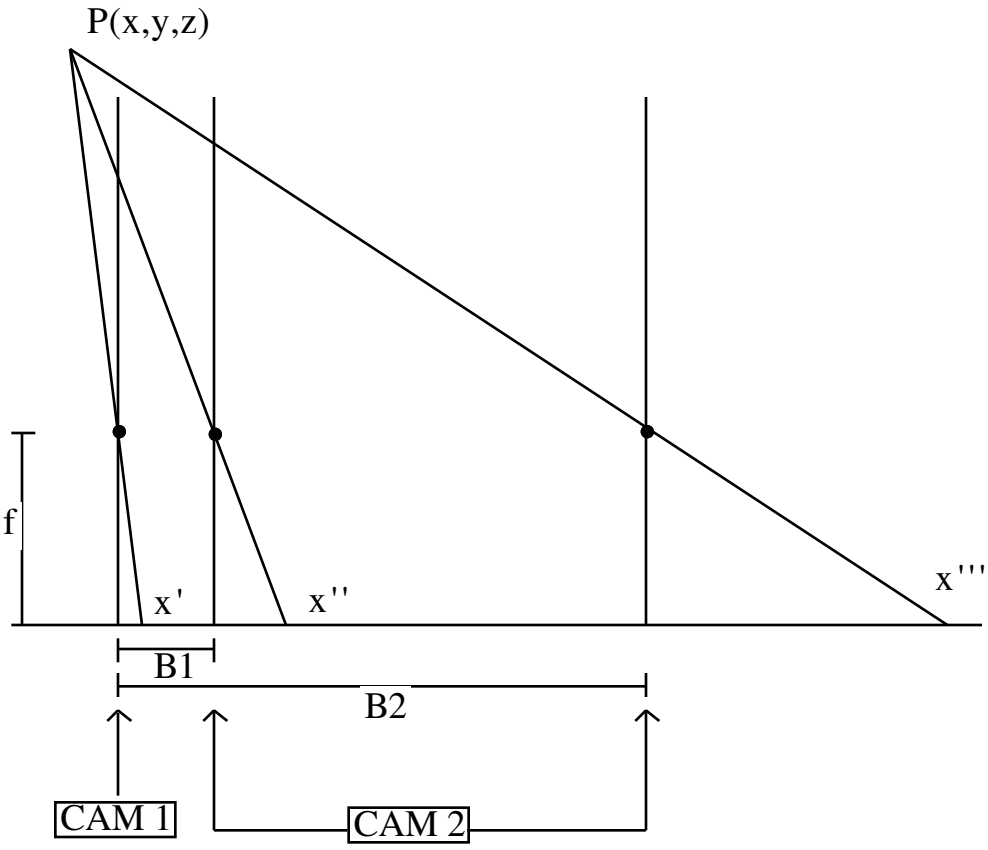
VARIABLE BASELINE STEREO

- Active control of baseline separation

- Fundamental tradeoffs:

$$\text{Baseline} \propto (\text{ease of matching})^{-1}$$

$$\text{Baseline} \propto \text{depth resolution}$$



BASELINE SELECTION IN FOVEA

OLD APPROACH:

- Conservative "worst case" strategy to guarantee unique matching

$$B = \frac{(D+f)\Delta x}{2f} \text{ with } \Delta x = 1 \text{ pixel}$$

where,

B = Stereo Baseline
D = Minimum distance to platform
Δx = disparity

- Expand by a fixed amount at each stage

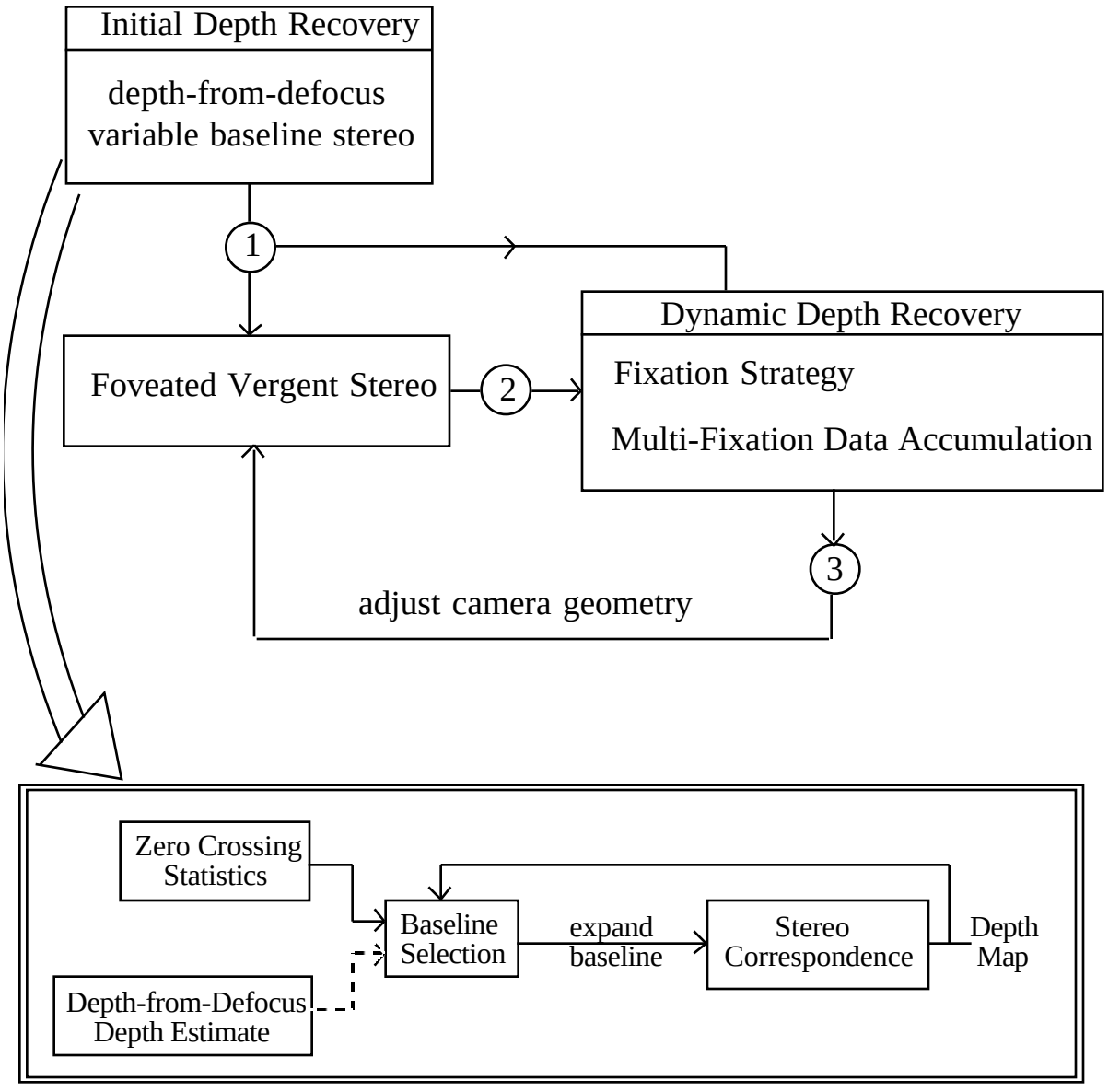
FOVEA'S APPROACH:

- *Adapt* to current scene information
- Use the image information to determine the minimum matching primitive separation (T_{min})
- Set baseline accordingly

$$B = \frac{(D+f)(T_{min}-1)}{2f}$$

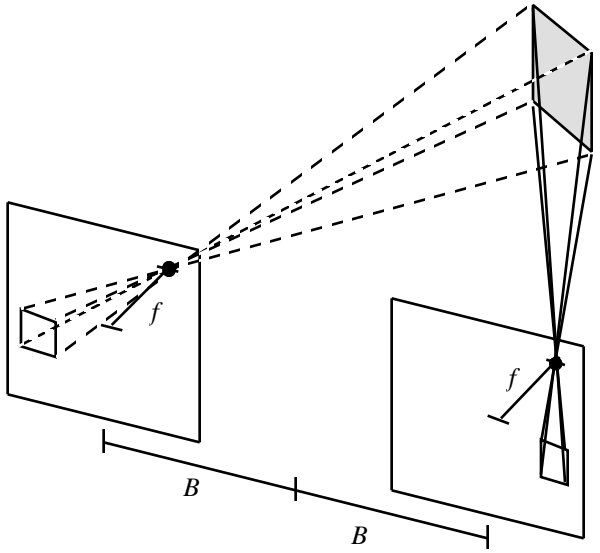
- Set expansion factor according using current disparity map to guarantee unique matching

INITIAL DEPTH RECOVERY



SURFACE PATCH DEPTH MAP

- Begin with disparity map from IDR process
- Disparity map can be converted to depth directly or converted to surface depth patches



- Disparity patches constructed using least square error fitting of MxM pixel patches
- Planar surface patches parameterized by (p, q, d_0):

$$pi + qj + d_0 = d$$

- 32x32 pixel patches used
- minimum data threshold used

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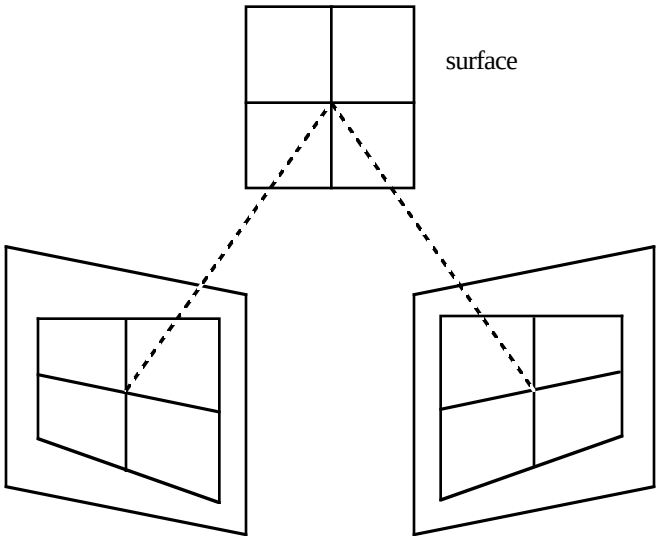
VERGENT STEREO



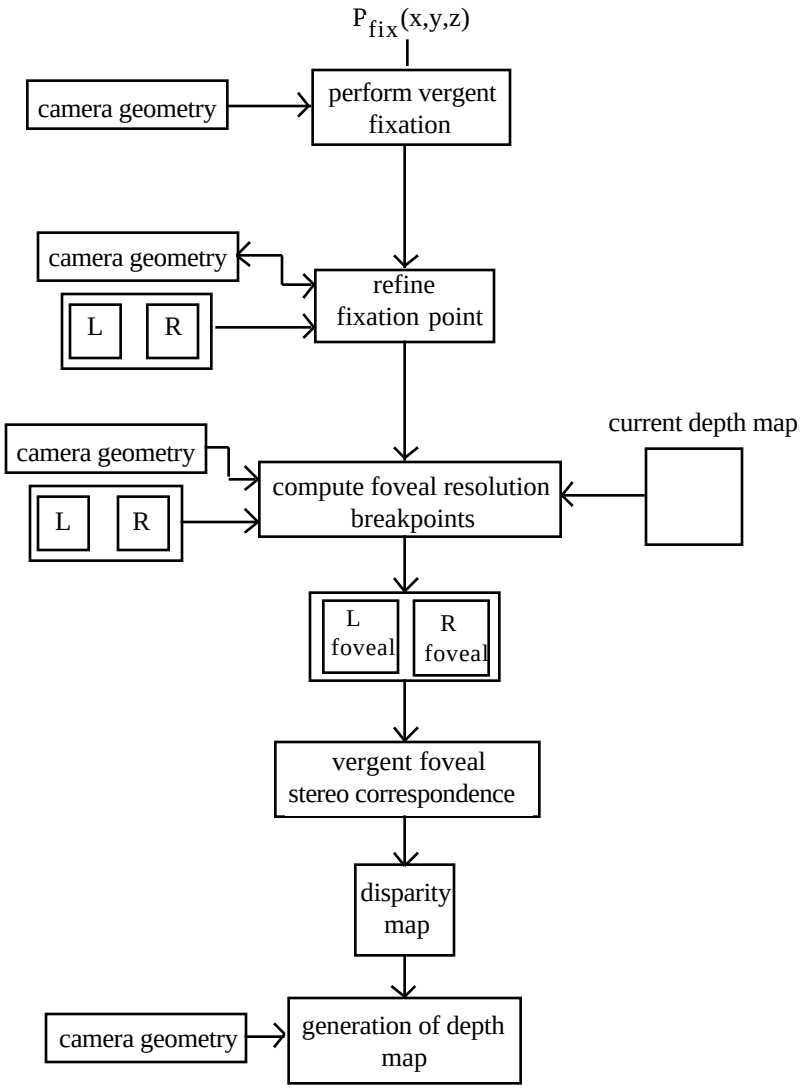
Advantages:

- **Aligned / Overlapping views** of surface
- **Natural correspondence** between central image regions
- **Improved** depth **resolution**
- Melds with **fixation strategies**
- Melds with **foveal processing** for reduced data load

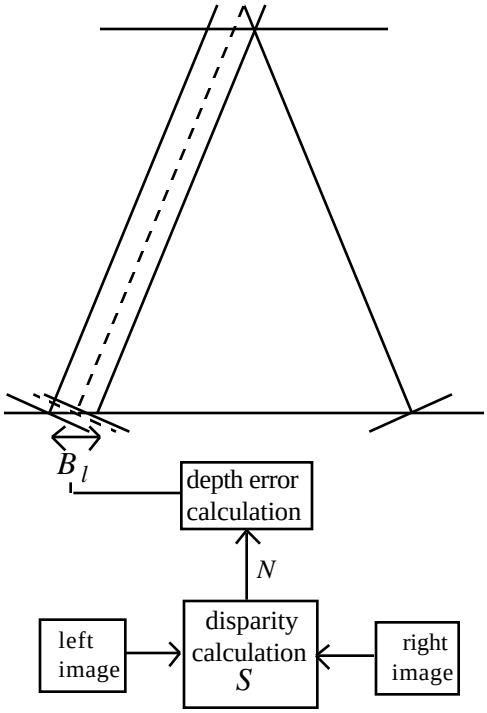
Complications:

- **Need support** to perform accurate vergence
- Peripheral **correspondence complicated** by **perspective projection**

FOVEATED VERGENT STEREO PROCESS



REFINE FIXATION POINT



- **Control baseline** position to **align cameras** on surface
- Expression for **current depth**

$$Z = \frac{\left(f\cos\theta - D_h N_x \sin\theta\right)}{\left(D_h N_x \cos\theta + f\sin\theta\right)}\left(f\sin\theta - \frac{\left(B_l + B_r\right)}{2}\right) - f\cos\theta$$

- Move to reduce D_h to 0

VERGENT STEREO IN FOVEA

To perform correspondence must either

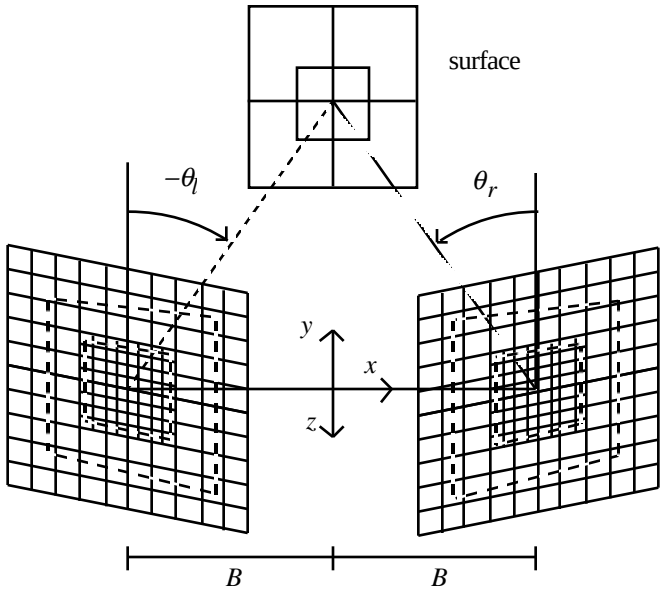
- **change correspondence process** to match new epipolar lines
- change images (*rectify*) to fit parallel baseline scanline correspondence

OR

- Use a multiresolution *foveal* processing structure to maintain scanline matching

FOVEATED VERGENT STEREO

- **Trade depth resolution** for **matching simplicity** in the periphery
- Maintain **high resolution** in **central foveal** region

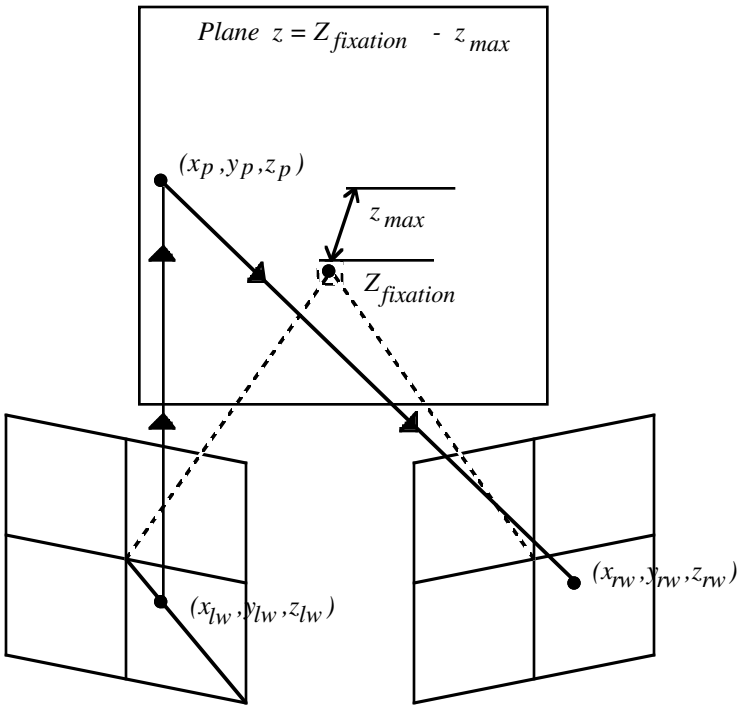


- The critical question:

  How to determine the foveal processing structure?

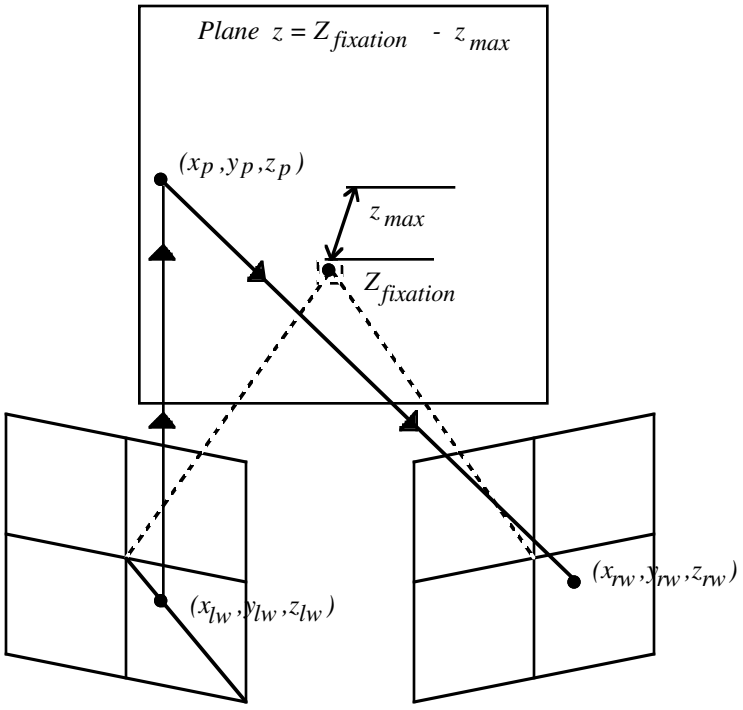
CONSTRUCTION OF FOVEAL ARRAY

- Depends on **camera geometry** and surfaces in view
- Must **constrain local scene** structure to guarantee correspondence
- Constraint placed on range of furthest surface from fixation point (z_{max})
- Given current camera geometry can compute the *breakpoints* that divide different resolution levels



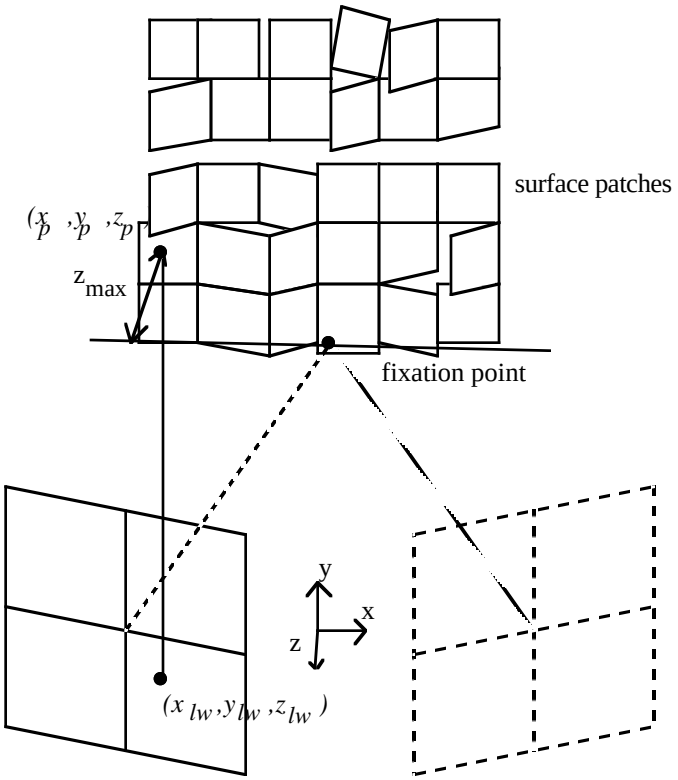
COMPUTATION OF RESOLUTION BREAKPOINTS

- For a chosen z_{max} :
  - **compute intersection** for backprojected image point with plane
  - **compute intersection** of forward projection of this intersection with right image plane
  - **Set breakpoints** when disparity increases past one-half the current resolution



REFINEMENT OF FOVEAL DESIGN

- Use **current / accumulated depth map** to determine z_{max}
- **Raytrace current surface** at low resolution
- Take maximum distance from fixation point as z_{max}



STEREO CORRESPONDENCE IN FOVEA

Two Algorithms tested with system:

- **Deterministic Search**

  For each feature point $L(i,j)$ compute l_2-norm $S(i,j,d)$:

$$S(i,j,d) = \sum_{u=-\frac{M}{2}}^{\frac{M}{2}} \sum_{v=-\frac{M}{2}}^{\frac{M}{2}} \left[\frac{L(i+u, j+v)}{\overline{L}} - \frac{R(i+u.\, j+v+d)}{\overline{R}} \right]^2$$

  S is computed for each disparity over range
  $(D_{min}<d<D_{max})$

  Minimum $S(i,j,d)$ chosen

- **Simulated Annealing**

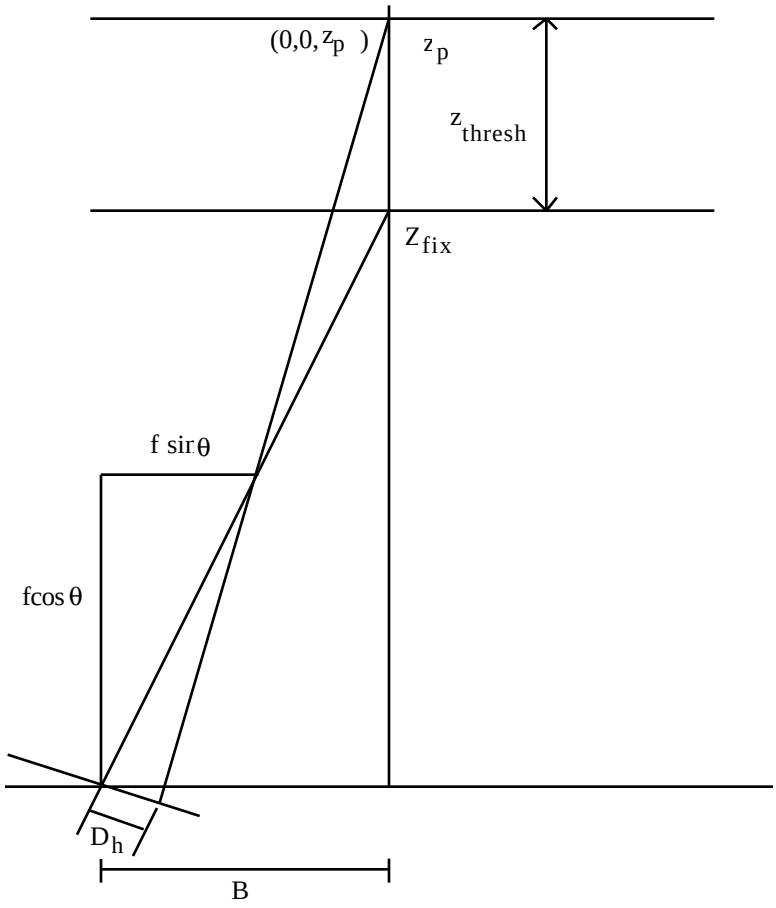
  Correspondence defined as energy minimization

  E = photometric term + (λ)(disparity smoothness)

$$E = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \left\{ \left| L(i,j) - R[i, j + D(i,j)] \right| + \lambda \sum_{u=-M}^{M} \sum_{v=-M}^{M} \left| D(i,j) - D(i+u, j+v) \right| \right\}$$

REFINEMENT OF FOVEAL DESIGN

- Need a method to appropriately set z_{max}
- Set a threshold (z_{thresh}) for the computation of depth



- Compute correspondence only within this range

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DYNAMIC DEPTH RECOVERY PROCESS IN FOVEA

Composed of two components:

- **Probabilistic Fixation Strategy**

  --evaluation of competing criteria for fixation
  --**selection** of **new fixation** site

- **Multi-Fixation Data Integration and Access**

  --integrate new surface patches
  --provide access to data for outside processes

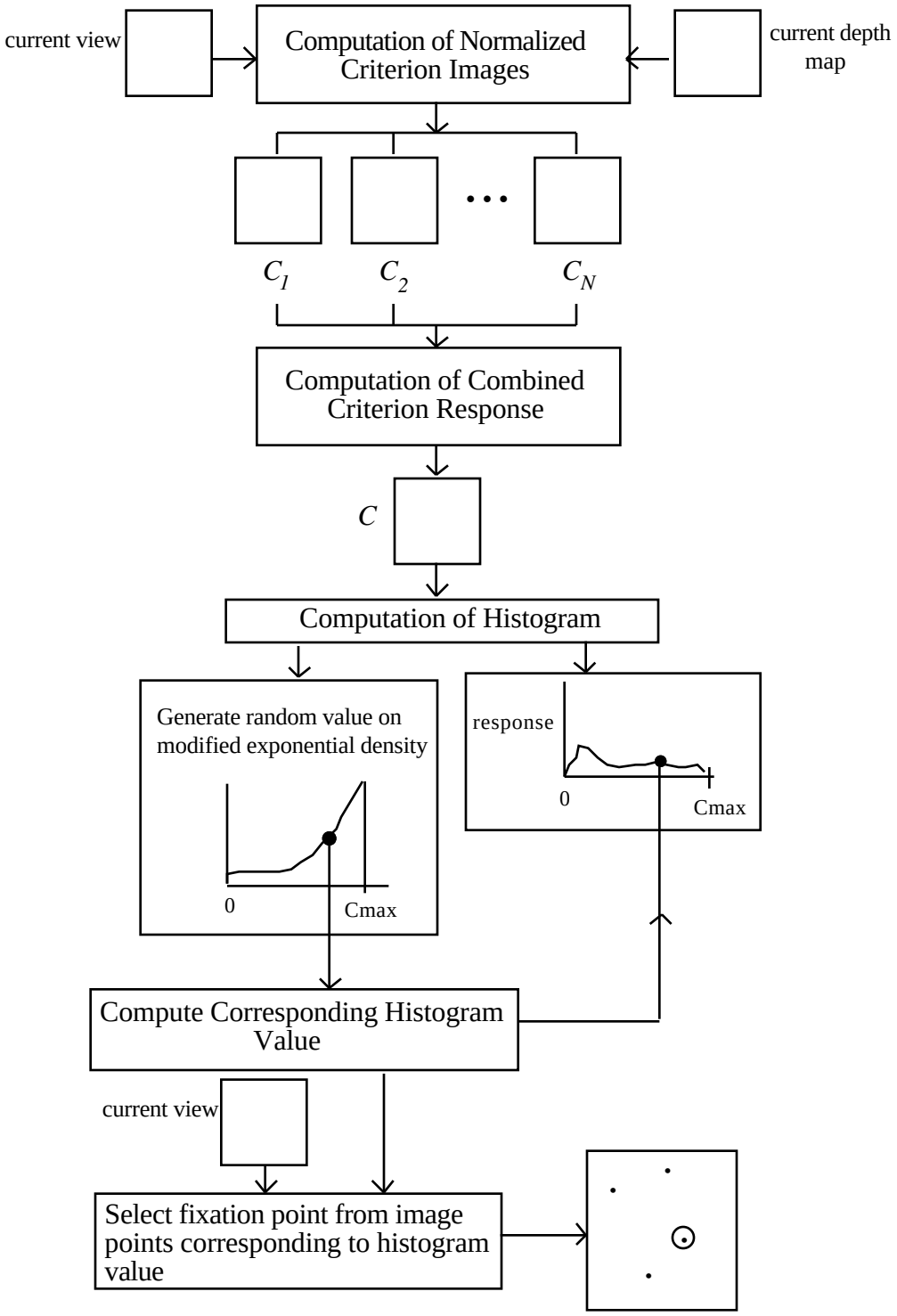
FOVEA'S PROBABILISTIC FIXATION STRATEGY

GOAL: Select the **next site** for fixation, based on the **current view** and the **accumulated depth map**

Advantages:

- Integration of 2-D and 3-D criteria in a consistent fashion
- Dynamic selection of next fixation point
- Modular Structure

PFS BLOCK DIAGRAM



FIXATION POINT SELECTION CRITERIA

- **Gradient attraction**

$$C(i,j)_{grad} = \left|\nabla I(i,j)\right|^2 = \left[I(i,j) - I(i,j-1)\right]^2 + \left[I(i,j) - I(i-1,j)\right]^2$$

- **Local Suppression**

$$(i,j)_{local\ sup} = \begin{cases} 1.00 & \text{if the point has not been mapped at foveal resolution} \\ 0.01 & \text{otherwise} \end{cases}$$

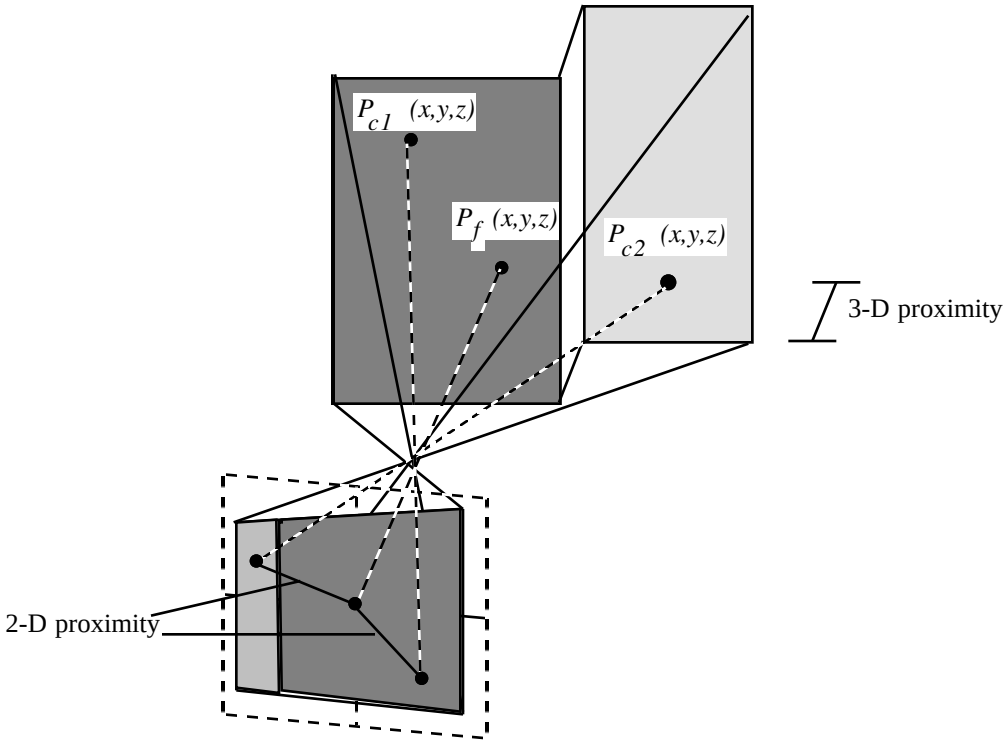
$$C(i,j)_{wander} = \begin{cases} 1.00 & \text{if the point is in the mapping range} \\ 0.01 & \text{otherwise} \end{cases}$$

- **Proximity**

$$C(i,j)_{2-D\ Proximity} = e^{-\alpha\sqrt{(i-i_c)^2+(j-j_c)^2}}$$

$$C(i,j)_{3\text{-}D\ proximity} = \begin{cases} 1.0 & \text{if within } z_{thresh} \text{ of fixation point} \\ 0.1 & \text{otherwise} \end{cases}$$

SELECTION CRITERIA-- PROXIMITY



- **2-D proximity criterion** keeps fixation **point near current position**
- **3-D proximity criterion** keeps fixation point on current surface

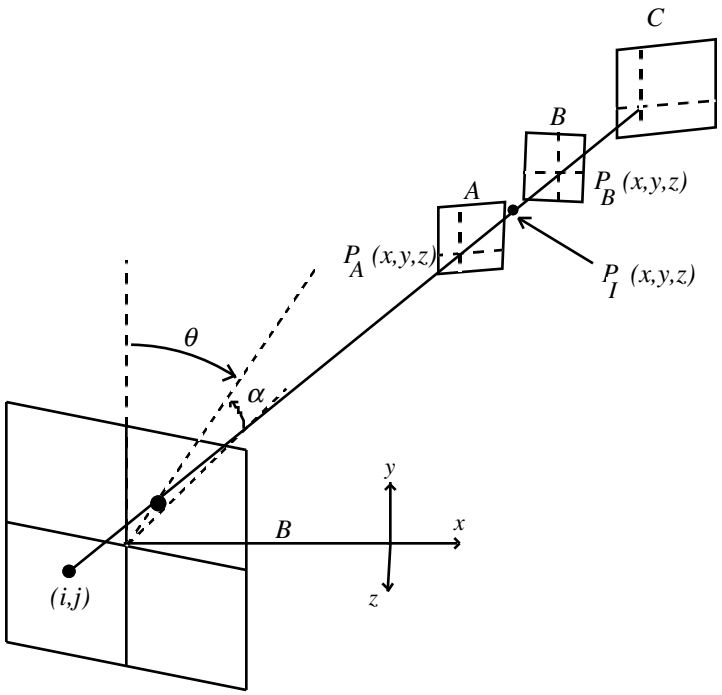
DATA INTEGRATION AND ACCESS

Two Approaches:

- Accumulated Surface Patch Structure

  --All patches are included in data structure

  --Depth is disambiguated by raytracing current view:



- Condensed Surface Patch Structure

  --Only most recent / highest resolution data integrated

  --Data integrated in a hierarchical fashion

CONCLUSION

CONTRIBUTIONS:

- The creation of an autonomous system for 3-D scene recovery with

  --integration of surface information over multiple fixations

  --depth recovery using a vergent geometry

  --integration of multiresolution surface information

- Two new methods for Initial Depth Recovery
  - -Adaptive Variable Baseline Stereo
  - -Maximum-Likelihood Depth-from-Defocus

- Novel technique for performing vergent stereo correspondence
  - --Foveated Vergent Stereo

- Adaptive fixation strategy for computing next view
  - --Probabilistic Fixation Strategy