An Endoscope With 2 DOFs Steering of Coaxial Nd:YAG Laser Beam for Fetal Surgery

[Yamanaka *et al.* 2010, IEEE trans on Mechatronics]

Automatic Tracking Algorithm in Coaxial Near-infrared Laser Ablation Endoscope for Fetus Surgery

[Hu *et al.* 2014, International Journal of Optomechatronics]

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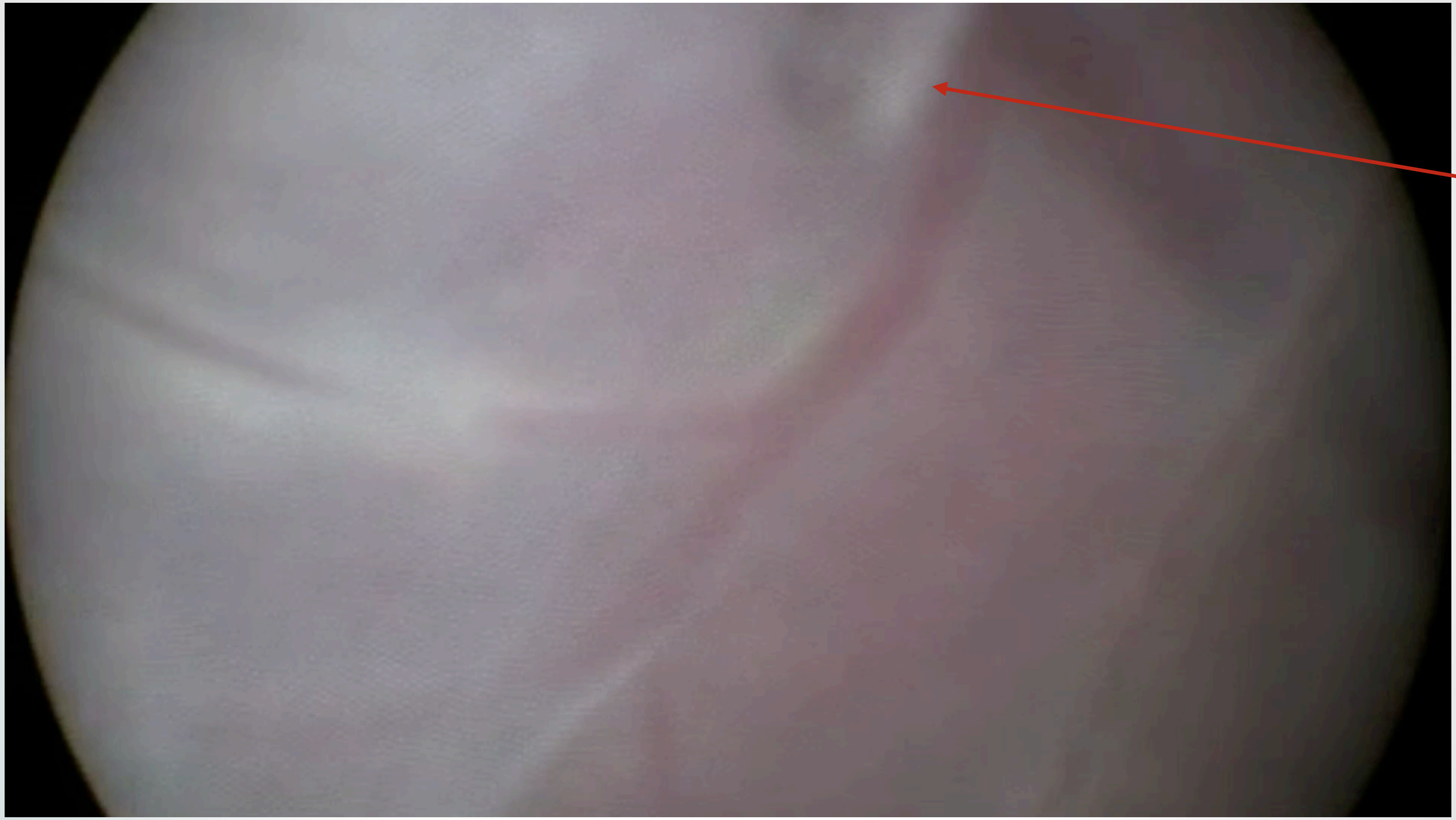
Clinical Motivation

- Twin to Twin Transfusion Syndrome
  - Uneven blood flow between twins sharing a placenta
  - High Mortality rate
- Treatment: Fetoscopic Laser Photocoagulation
  - Laser fibre introduced endoscopically
  - Connecting blood vessels in the placenta are ablated

Current Procedure



Limitations and Aims

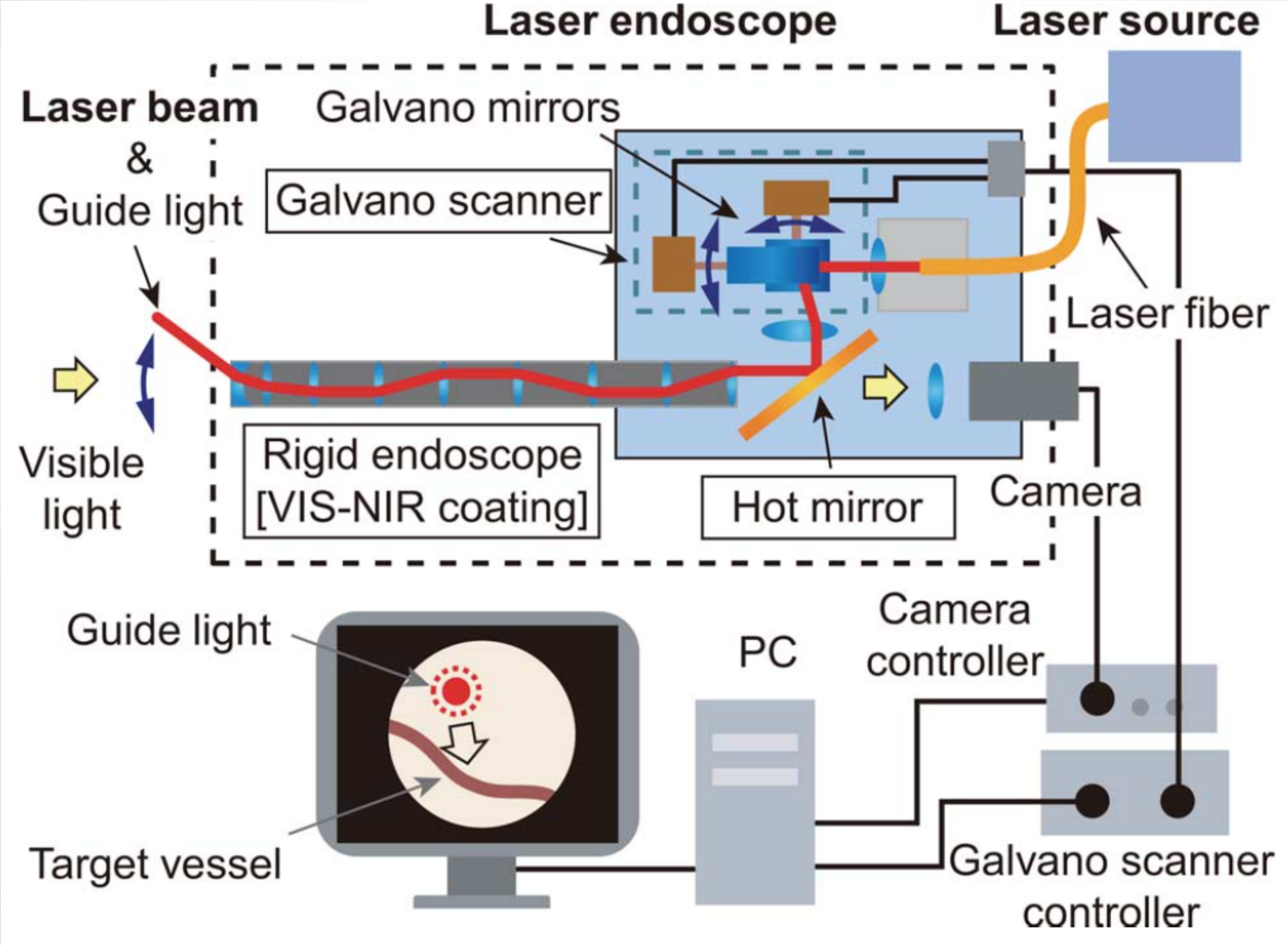
Current Limitations (Justifications)

- Fibre endoscopes require high power illumination
- Procedure requires high dexterity to target vessels
  - 2D images - unknown distance
  - Placenta is delicate

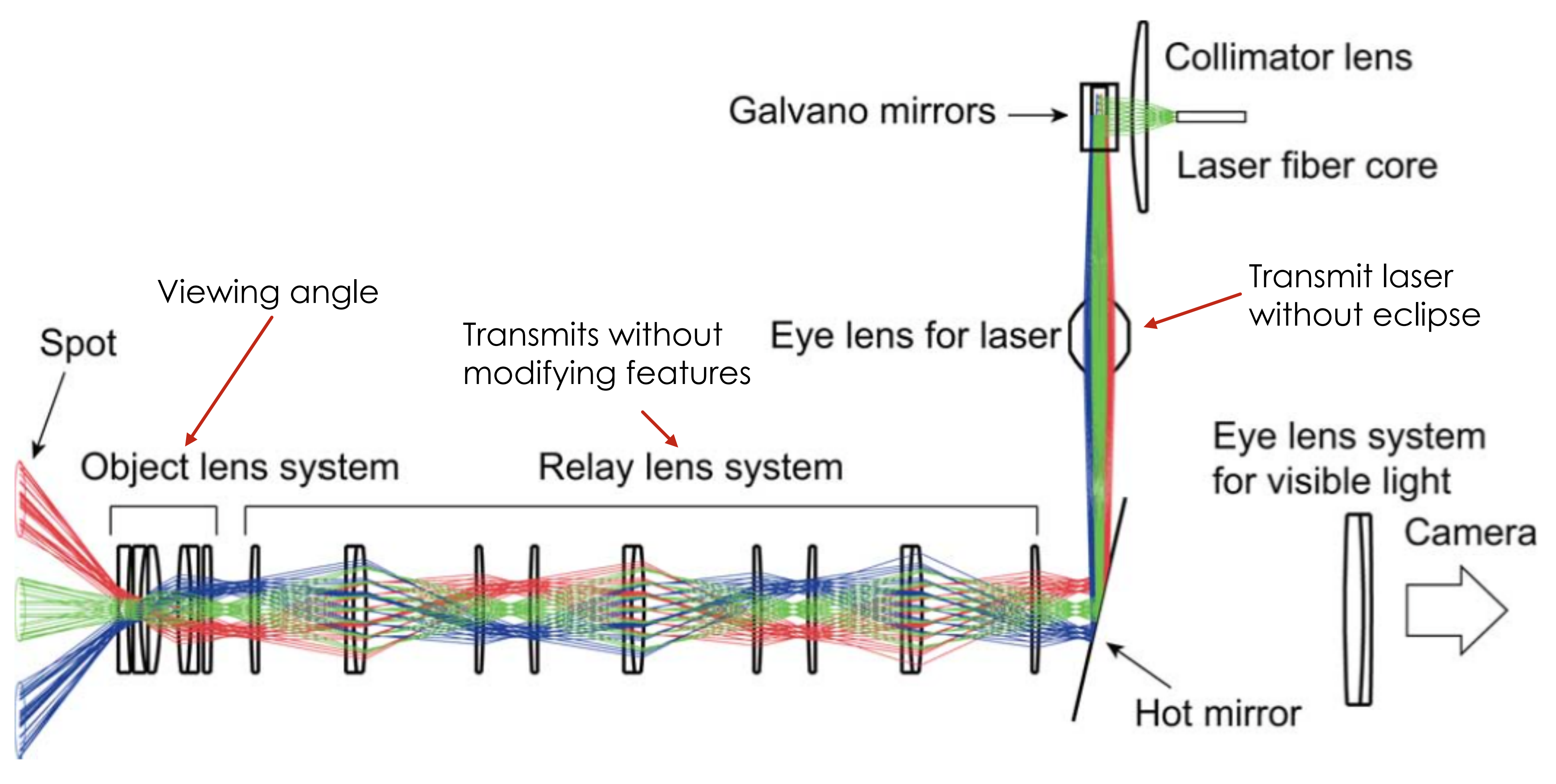
Aims

- Rigid Endoscope to reduce illumination required
- Target the laser without moving the endoscope

System Framework

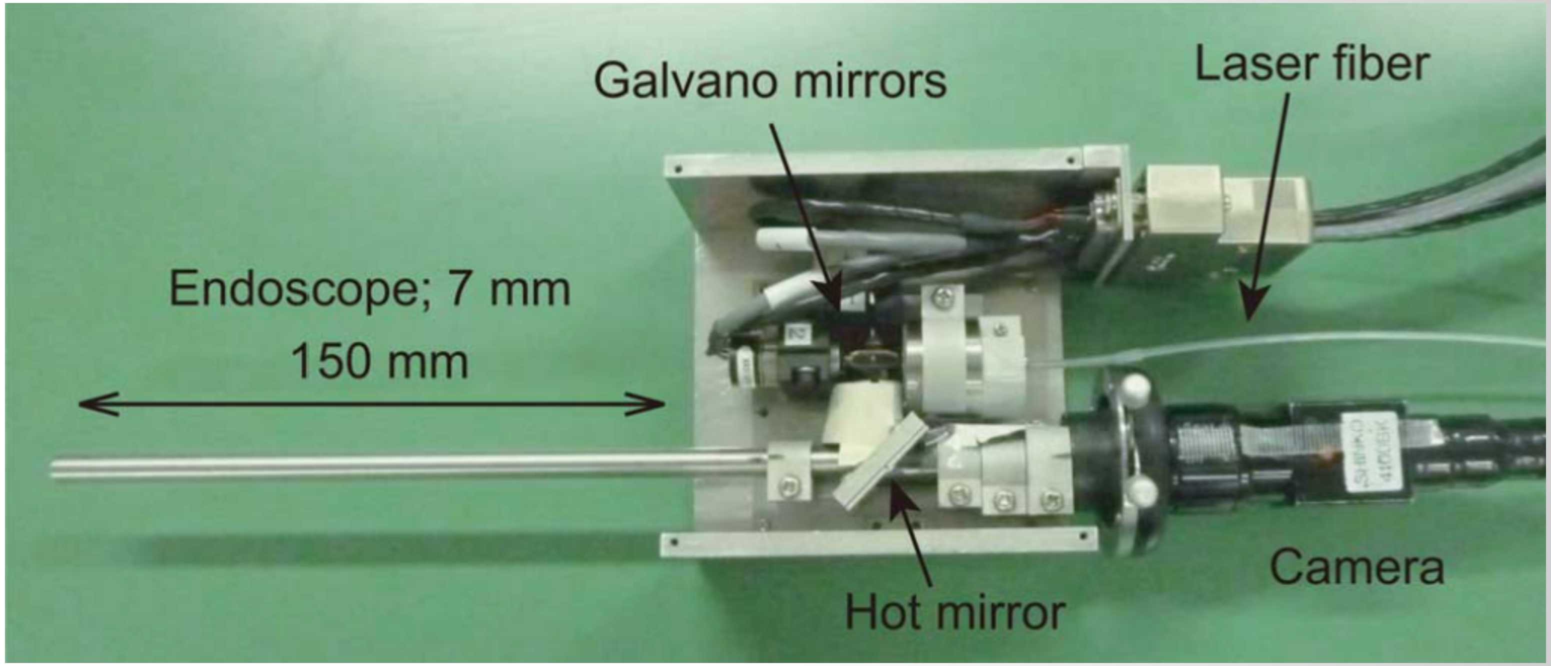


Optical System



Instrument

- FoV: 70°
- Laser Spot Properties
  - d = 10 mm, ∅ = 2.2 mm
  - d = 20 mm, ∅ = 3.2 mm
- No illumination channel
- 450g



Calibration

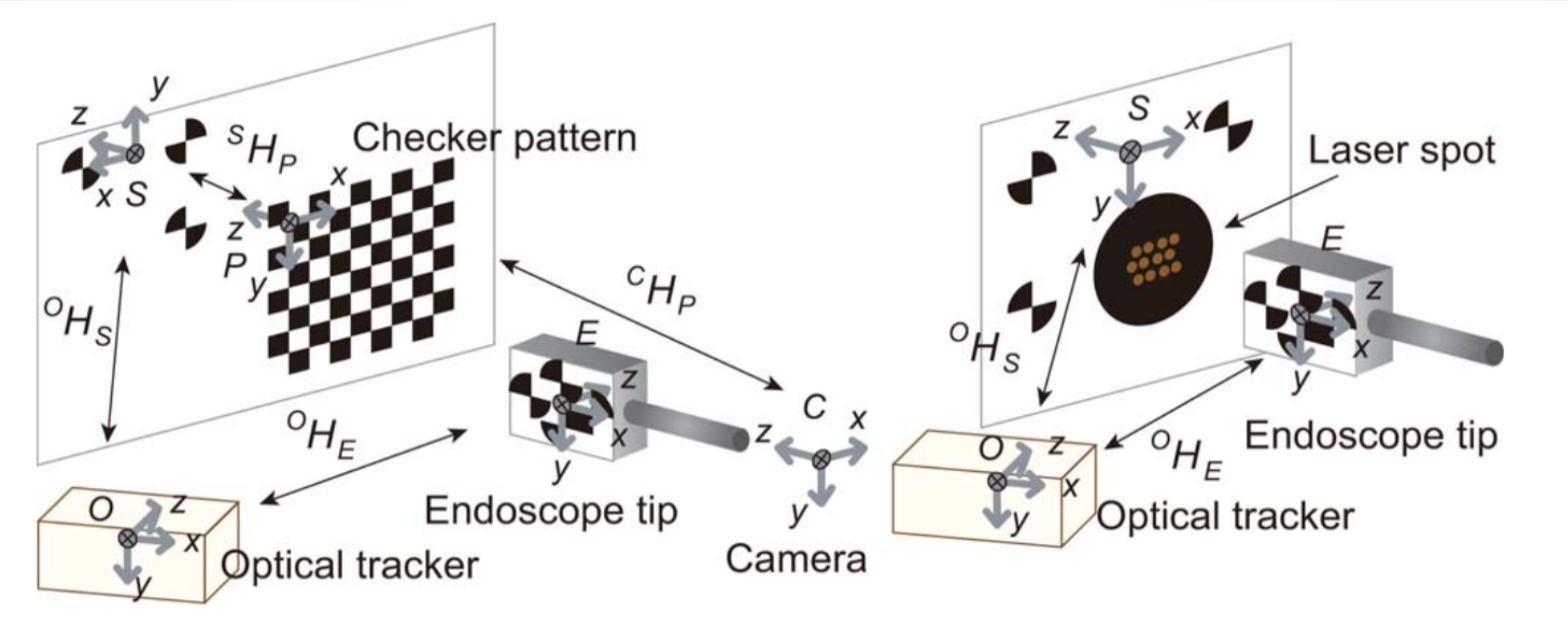


Image coordinates

Scale factor

Endoscope tip coordinates

Zhang, 2

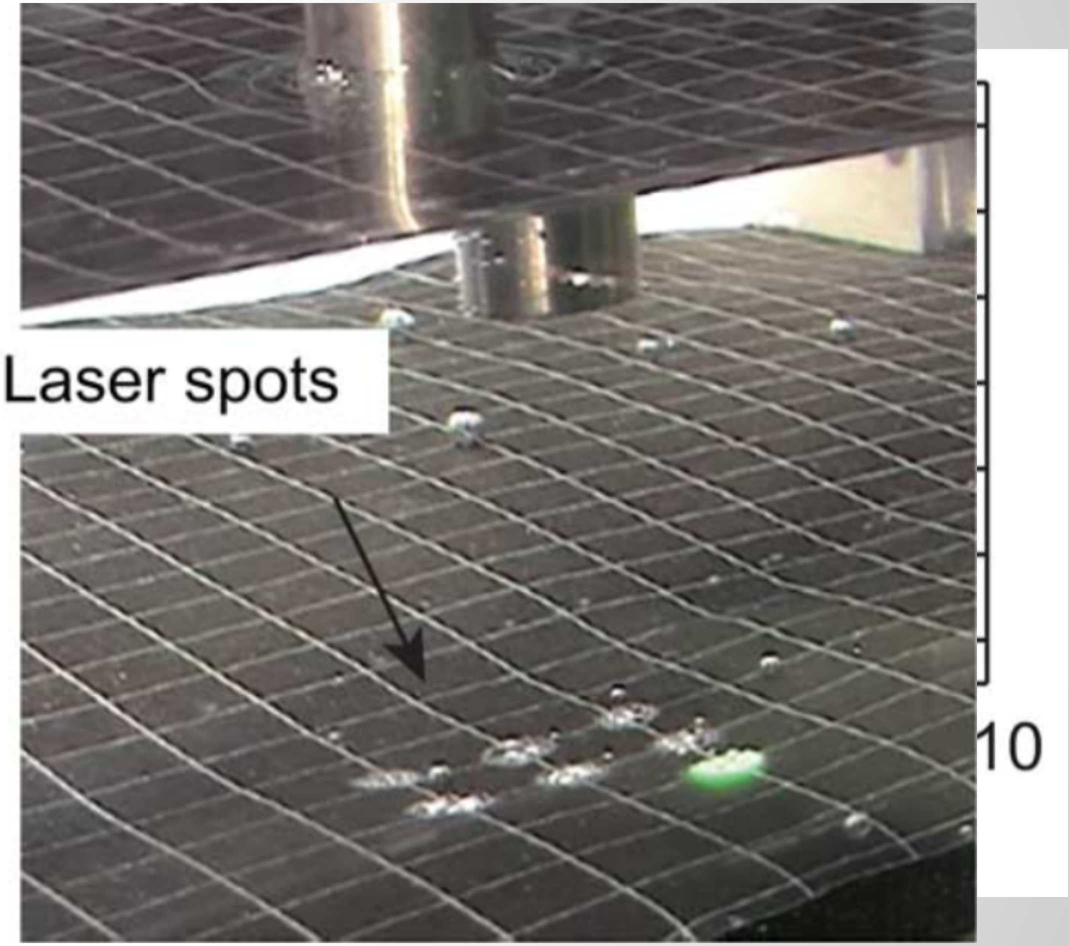
$$\lambda \begin{pmatrix} \tan \\ 1 \end{pmatrix} {}^E H_C = {}^O H_E^{-1} \, {}^O H_S \, {}^S H_P \, {}^C H_P^{-1} \begin{bmatrix} 0 & o_X & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

Intrinsic

Extrinsic

Results: Bench Testing

- Power
  - Transmission efficiency = 34%
  - Maximum laser power = 14.86 W (50 W)
- Area
  - 0.9 $P_{max:}$ d = 20 mm; x = 10.7 mm; y = 9.7 mm
  - Firing angles (optical axis)
    - x: -13 to 11; y: -16 to 6
  - Max intensity was out of principal point of mirrors
- Accuracy
  - Water test; sheet pitch 5mm; target intersections
  - Positioning Error(20 mm) = 0.3mm ± 0.2mm
  - Error > 1 mm near the edge of the FoV

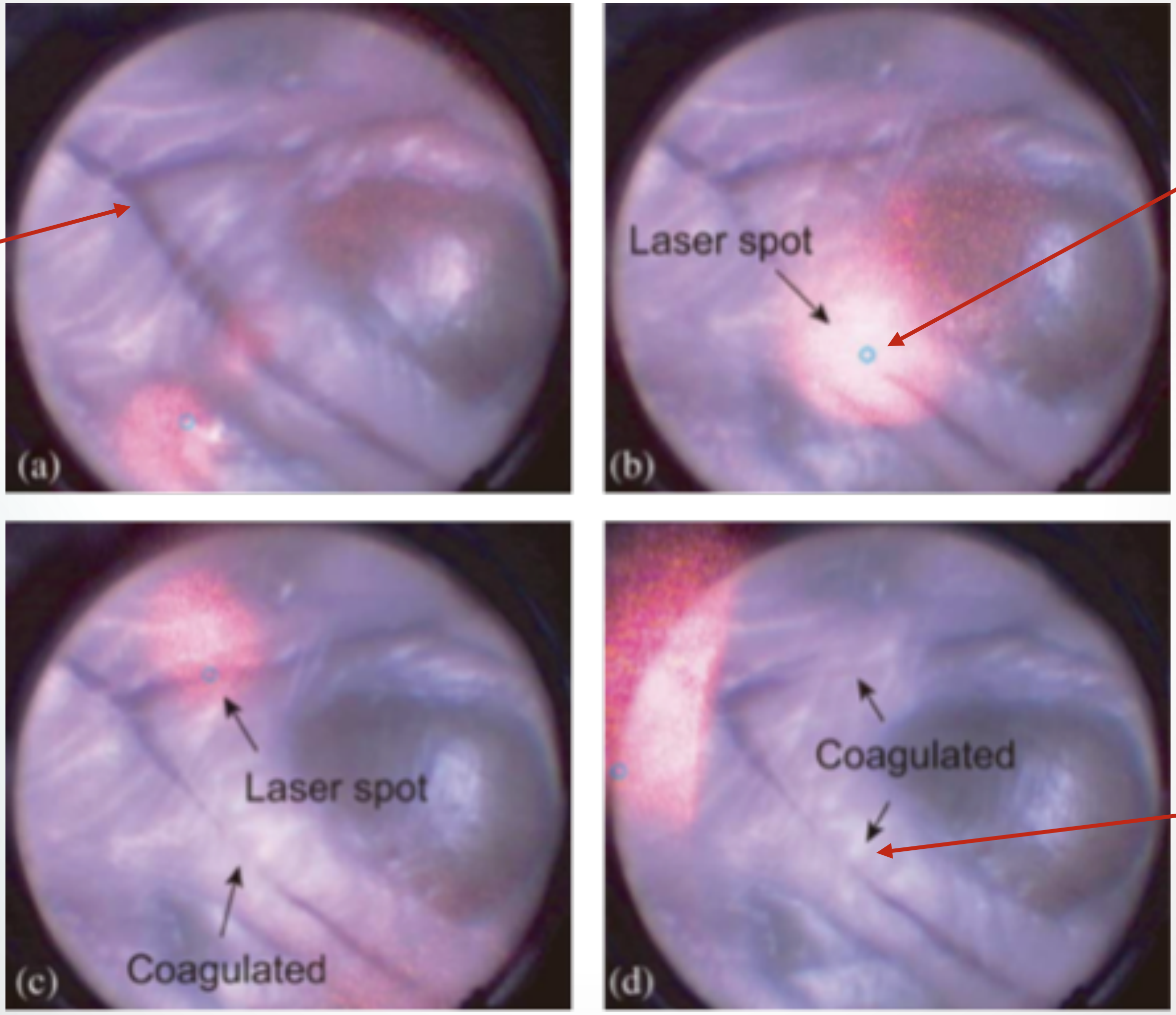


Power at 20 mm against optical angle

Results: *in vitro* Irradiation

Vessel diameter ≈ 0.8 mm

50W (source); 3s



Vessel diameter ≈ 0.3 mm

System Discussion

- Clinically used Systems
  - Rigid Curved Instruments
  - Manually manipulated
  - Diameter < 3mm
  - Built in light source
  - 2 instrument channels

- Presented System
  - Firing angles of over 20° horizontally and vertically
    - Misaligned
  - Large beam diameter (3.2 mm at 20 mm)
  - Diameter = 7 mm
  - No light source
  - 34% transmission efficiency

System Discussion

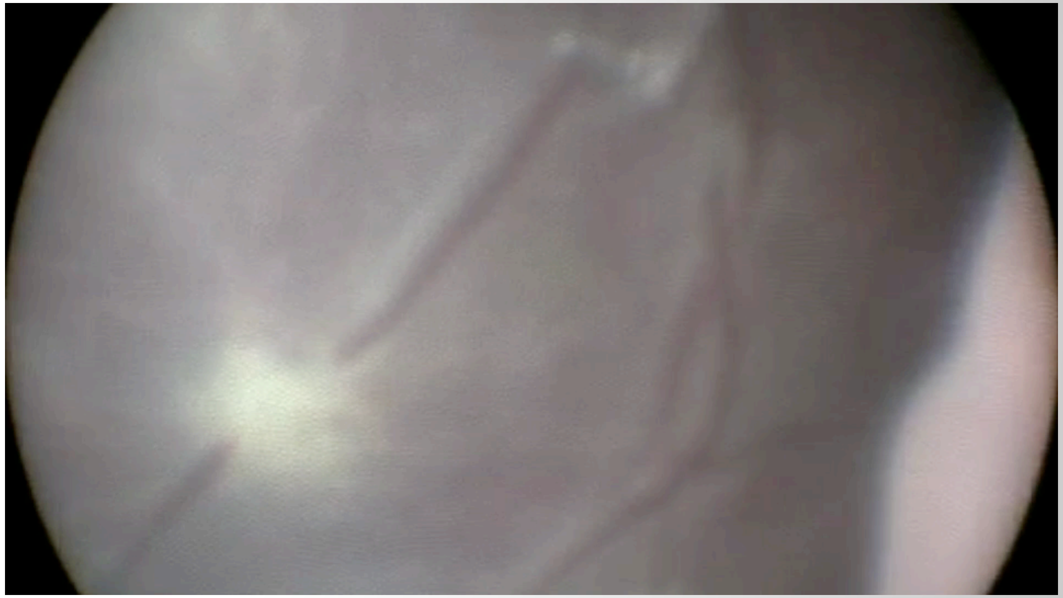
- Clinically used Systems
  - Rigid Curved Instruments
  - Manually manipulated
  - Diameter < 3mm
  - Built in light source
  - 2 instrument channels
- Future System
  - Refine manufacturing and placement of optics
  - Use of smaller optics to reduce size
  - Increase transmission efficiency

Automatic Tracking Algorithm in Coaxial Near-Infrared Laser Ablation Endoscope for Fetus Surgery

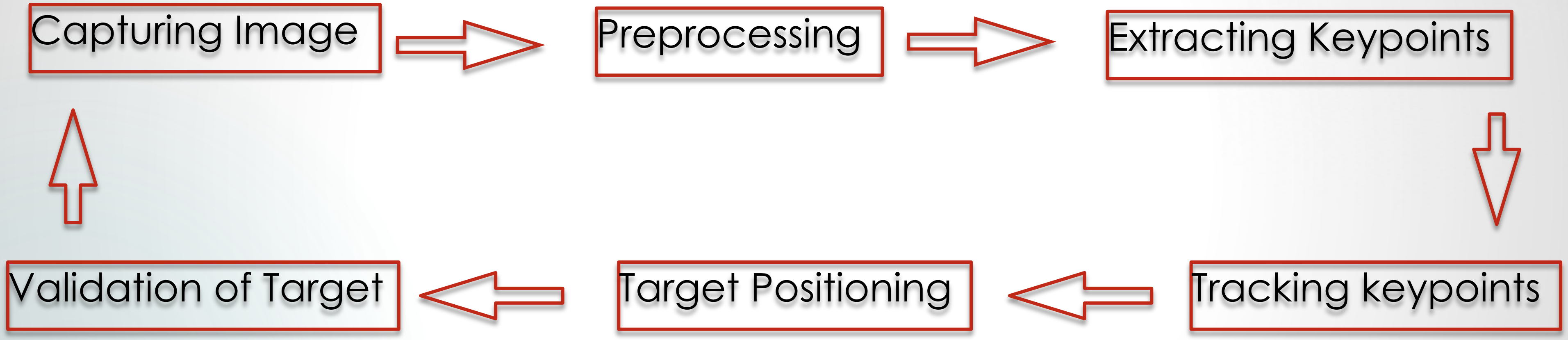
YAN HU, NORIAKI YAMANAKA & KEN MASAMUNE

Clinical Motivation and Aim

- Target point movement from respiratory and cardiac motion reduces accuracy
  - Respiratory arrest from general anaesthetic can be applied
    - Postoperative complications
  - For MRI scans, mother hold hers breath (20s)
  - Coagulation takes longer than 20s in total
- Solution
  - Object point tracking algorithm



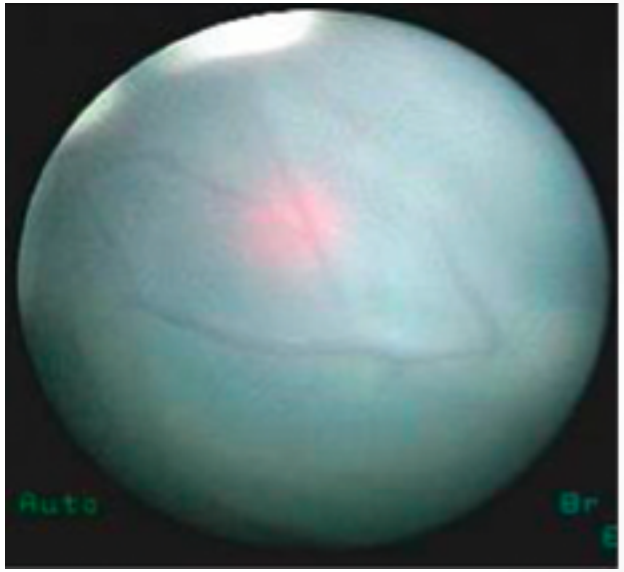
Proposed Algorithm

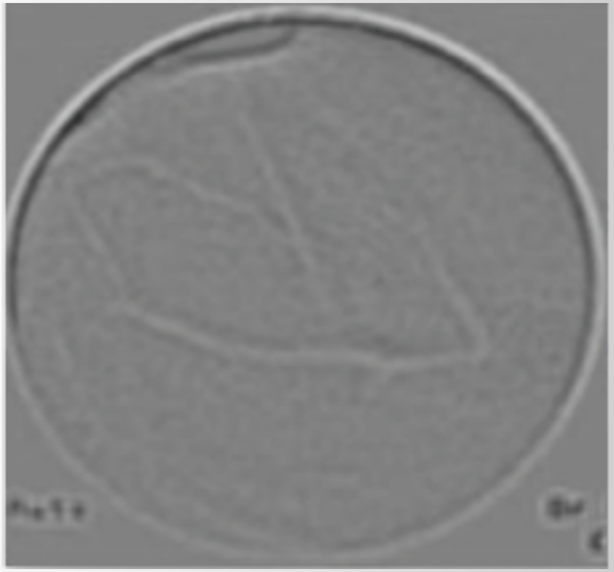


Speed is the main consideration

Preprocessing

- Camera Calibration (Zhang)
  - Remove distortions
  - Determine relationship
- Reduce image size
- Apply LoG filter to image
  - Find edges
  - Smooth
  - Grey scale

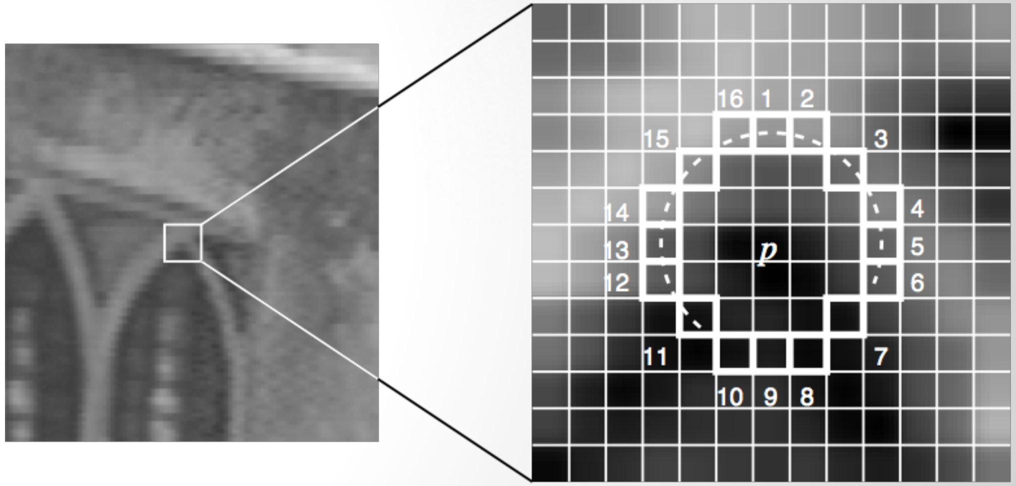




$$\mathrm{LoG} = \frac{x^2 + y^2 - 2\sigma^2}{2\pi\sigma^6} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right)$$

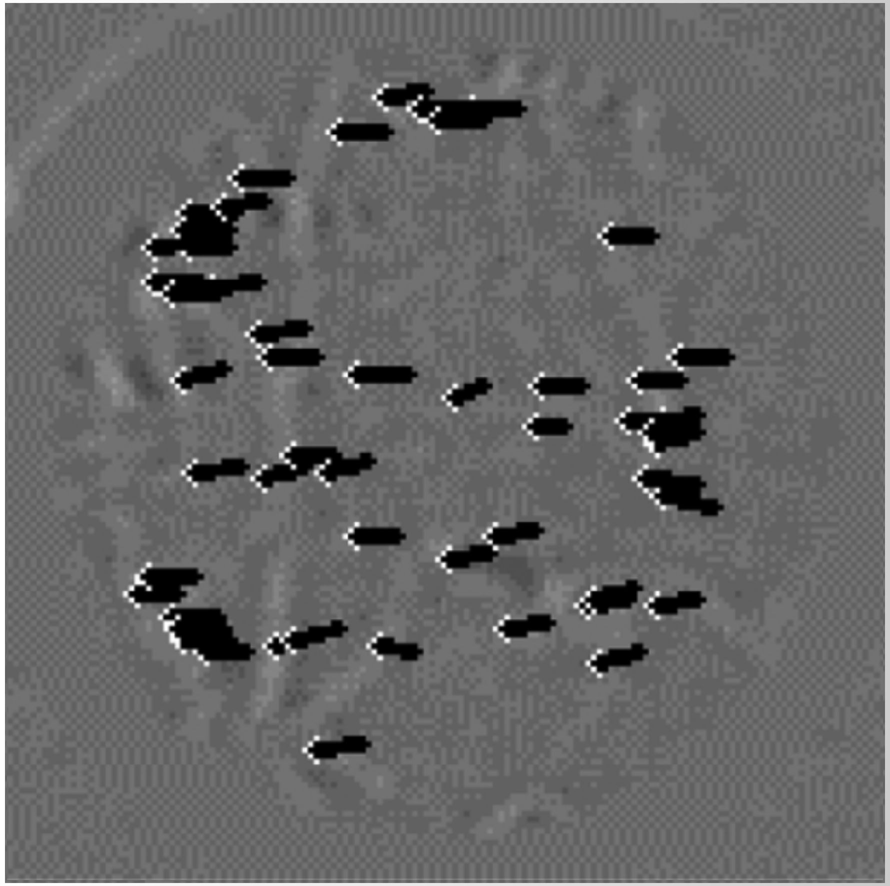
Extracting Keypoints

- Feature from Accelerated Segment Test (FAST)
  - High computational efficiency
  - Corner detecter
  - Intensity difference to threshold
  - For 768 x 288 image
    - FAST takes 1.5 ms
    - 50 times lower than SIFT



Tracking Keypoint

- Optical Flow
  - Track features from FAST
  - Pyramidal Implementation of Lucas-Kanade Optical flow
    - Finds the brightness gradient on a image neighbourhood
    - Mistaken points are removed by Random Sample Consensus Test using a homography matrix (**H**)



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Target Positioning

- Homography Matrix
  - Applies relationship between projection of H and relative positions of keypoints in the pre-frame

$$\lambda \begin{pmatrix} q_{cur} \\ 1 \end{pmatrix} = H \begin{pmatrix} q_{pre} \\ 1 \end{pmatrix}$$

  - q is object position
  - λ is the z axis when projected in 3D

Target Positioning

- Relative position of surrounding points
  - Current position can be calculated from:
    - The current keypoint position - s'_i
    - Relative position of the keypoint and object position of the pre-frame

$$q_t = \frac{\sum_i w_g(t_i) w_v(s'_i) \left(q_{pre} + t_i\right)}{\sum_i w_g(t_i) w_v(s'_i)}$$

    - W_g is weight from relative position, W_v is weight from distance to centre of image
    - $t_i = c_i - p_{pre}$

Target Positioning: Validation

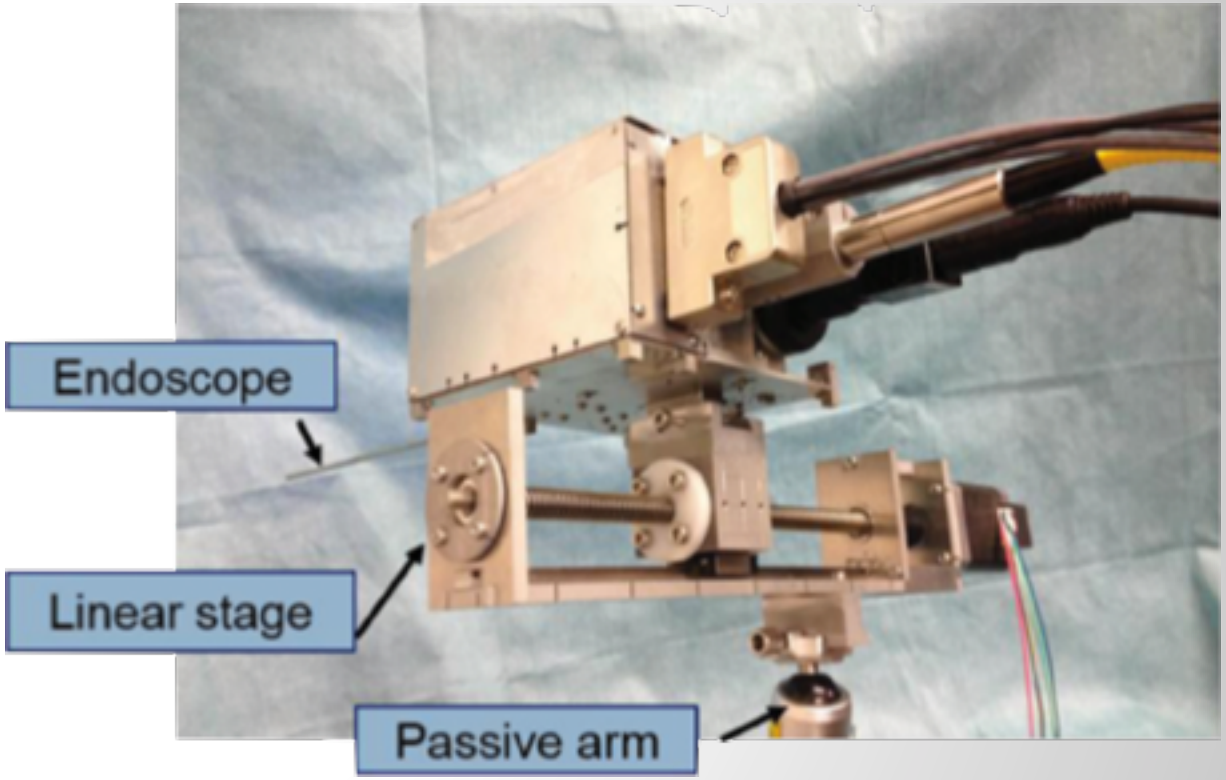
- Object position calculated using Homography
- If Homography cannot be counted on switch to relative positions
- Cross correlation coefficient calculated to ensure correct tracking

$$\mathbf{c} = \frac{\sum_{r_t < |q-p| \leq s} L_{cur}(p) L_{pre}(p)}{\sqrt{\sum_{r_t < |q-p| \leq s} L_{cur}(p)^2} \sqrt{\sum_{r_t < |q-p| \leq s} L_{pre}(p)^2}}$$

- Kernel size = 2s + 1; L is brightness of LoG image; p is point in kernel
- c > 0.85; object is tracked
- c < 0.85; object is lost; template matching is applied

Experiments

- Respiratory motion compensation
  - Modelled as sinusoidal motion
  - Assumed displacement of 10 mm
  - Maximum Velocity of 10 mm/s
  - Period of 4s
- Simulate movement by fixing object and moving endoscope
  - Tip displacement measured by a laser displacement sensor



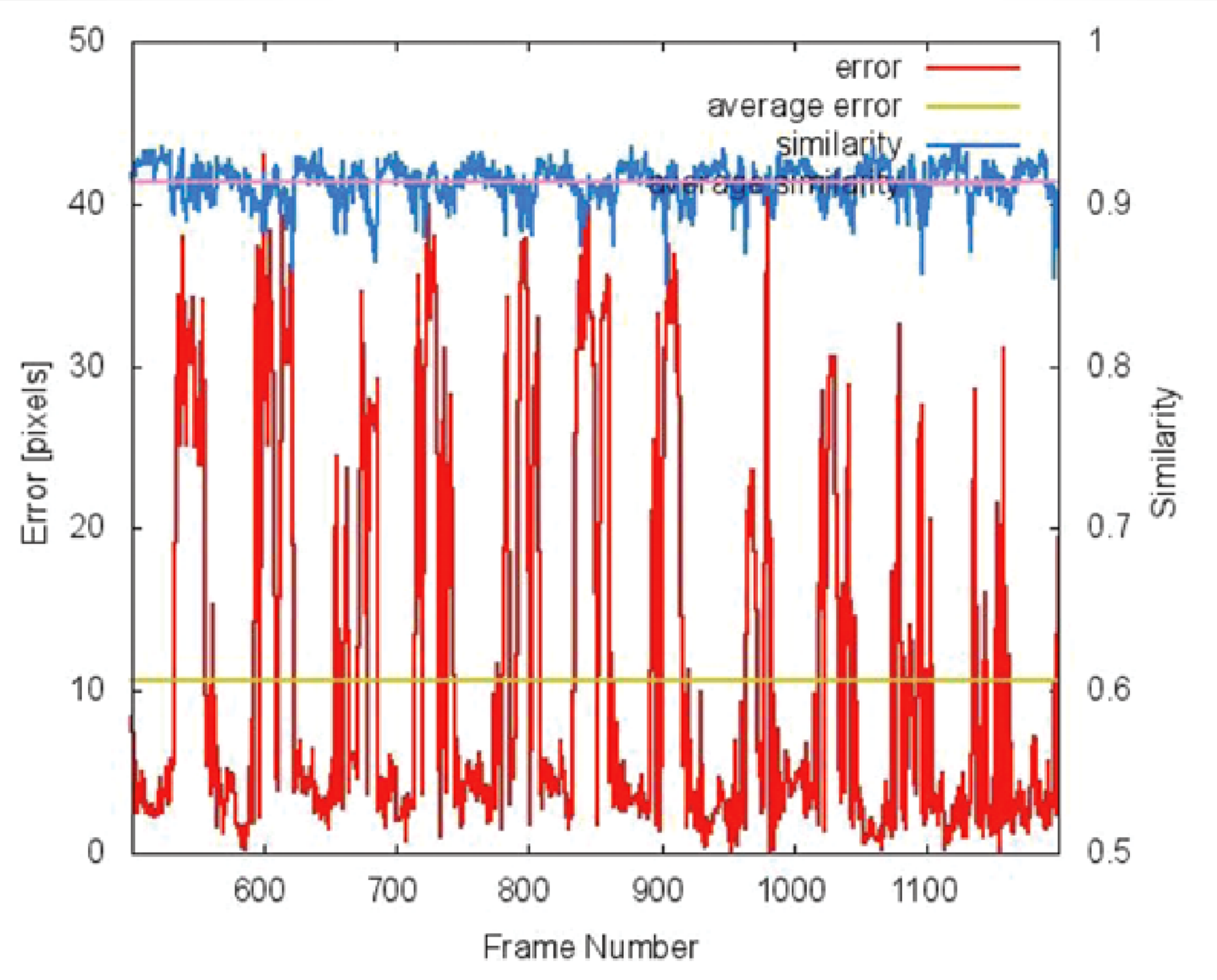
Results: in air

		Processing time [ms]	Similarity	Extracted points	Correctly tracked points	Tracking performance
Phantom	10 mm	30.89 ± 2.34	0.93 ± 0.05	86 ± 23	81 ± 23	100%
	15 mm	31.51 ± 2.05	0.95 ± 0.02	85 ± 19	79 ± 20	100%
	20 mm	31.75 ± 1.75	0.96 ± 0.02	86 ± 24	79 ± 20	100%
	30 degree	31.54 ± 2.57	0.92 ± 0.04	85 ± 21	80 ± 20	100%
Pig vessel	20 mm	44.66 ± 12.19	0.91 ± 0.01	176 ± 50	156 ± 48	50%

Camera frame rate is 30 fps

Results: in air

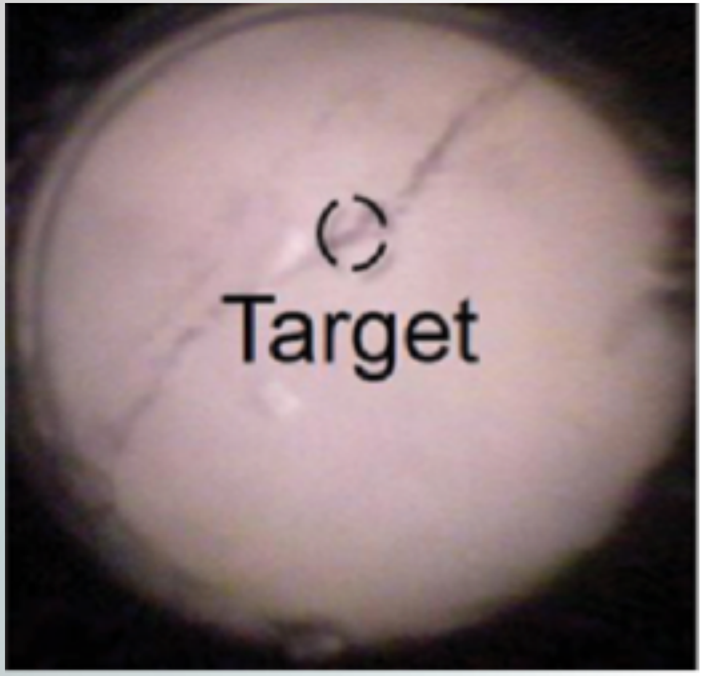
Pig Vessel Tracking Errors

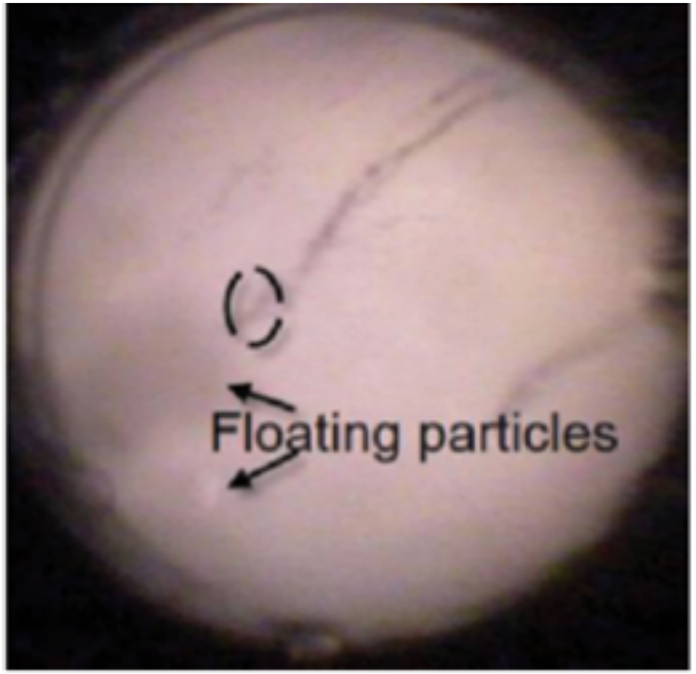


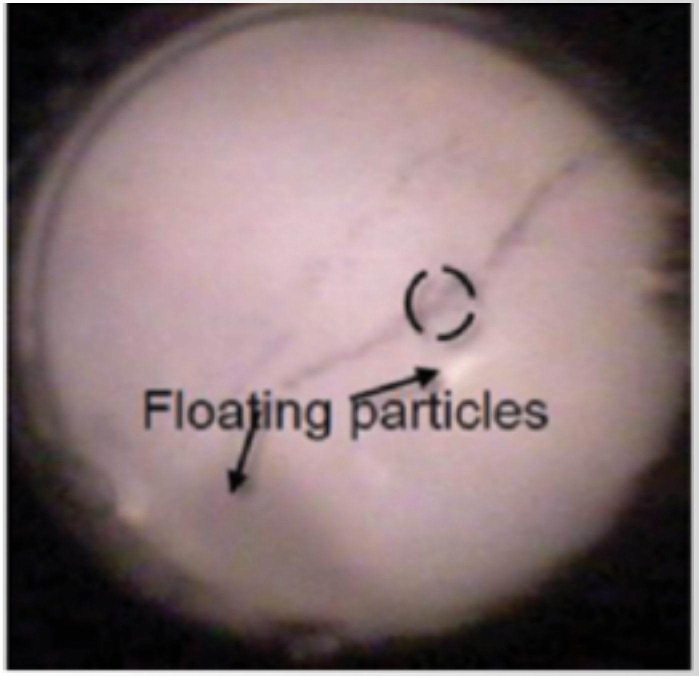
Experiments: under water

- Re-calibrate
- Distance set to 15 mm from centre of object
- Particles
  - Amniotic fluid particles, 1-2 mm in size at 35 weeks
  - TTTS is treated before 26 weeks
  - White paper cut to 1-2 mm is used to simulate particles
- Blurring
  - Blur caused by sudden motion viewed as shift-invariant blurring
  - Simulated using shift-invariant box filter (OPENCV)
  - Blur applied with kernel size of 5 and 11

Results: under water



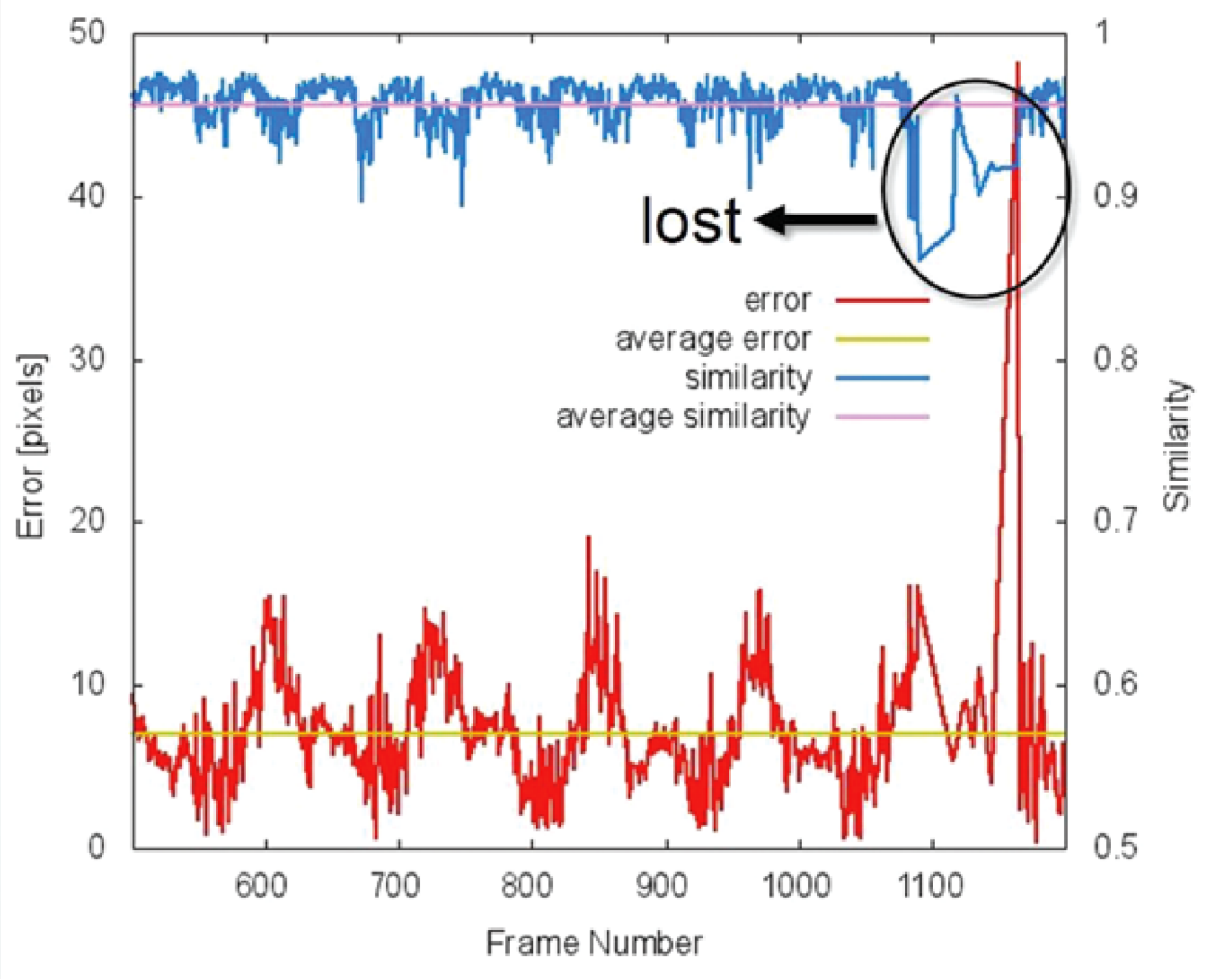




Results: under water

		Processing time [ms]	Similarity	Extracted points	Correctly tracked points	Tracking performance
Floating particles		26.31 ± 3.29	0.95 ± 0.01	82 ± 21	73 ± 21	91.39%
Blurring	Original	24.21 ± 2.54	0.96 ± 0.02	85 ± 18	78 ± 21	100%
	Kernel = 5	22.84 ± 1.79	$0.97 \pm .01$	84 ± 23	77 ± 20	99.16%
	Kernel = 11	23.55 ± 2.94	0.97 ± 0.01	97 ± 22	88 ± 24	97.63%

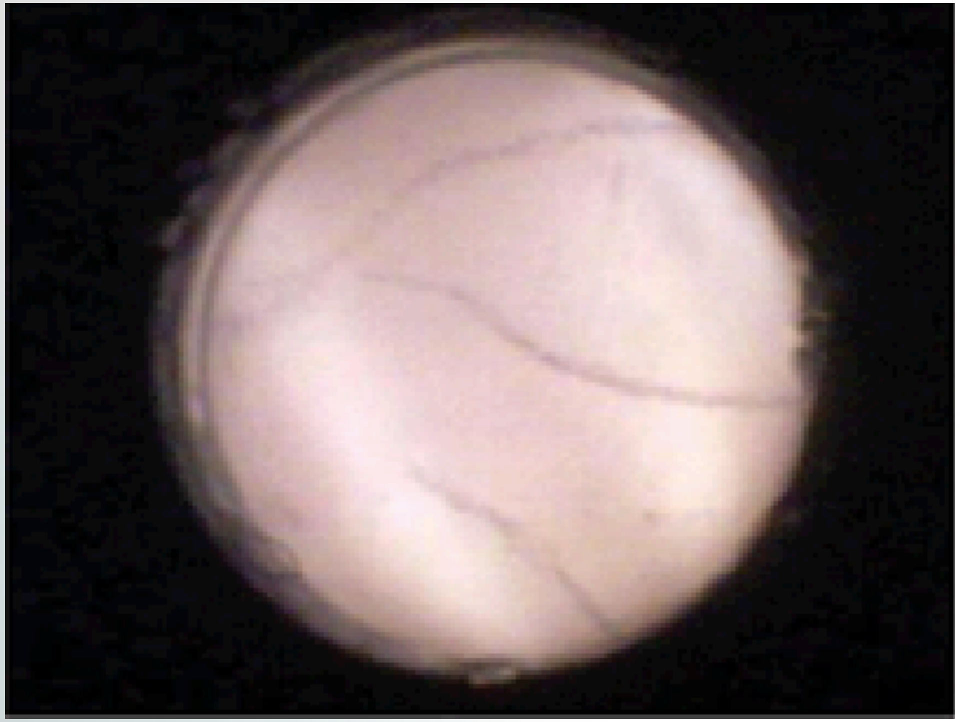
Results: under water

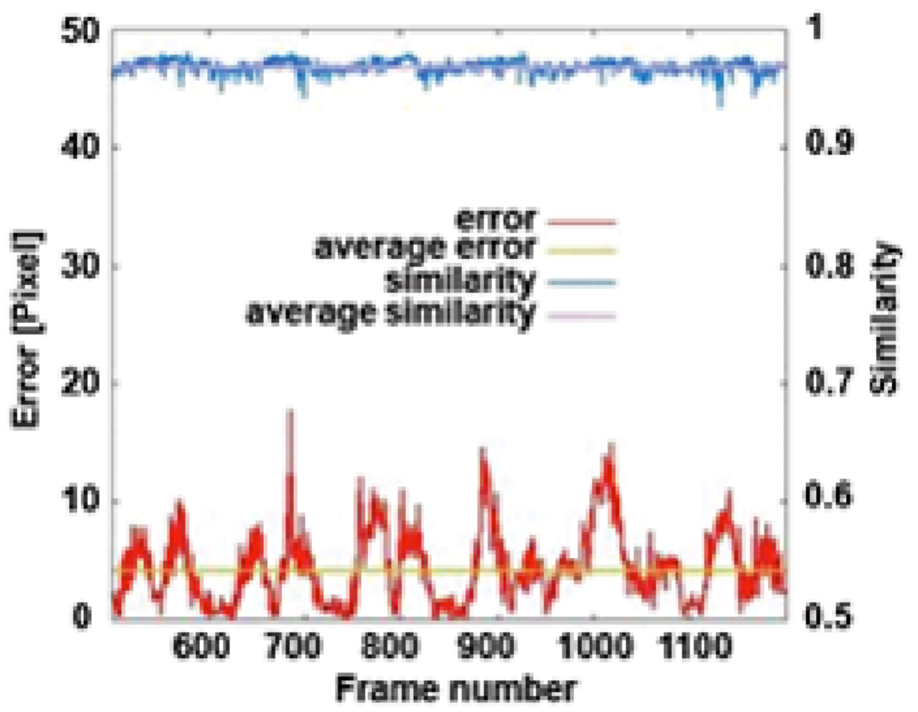


Tracking with Floating Particles

Results: under water

Blurring

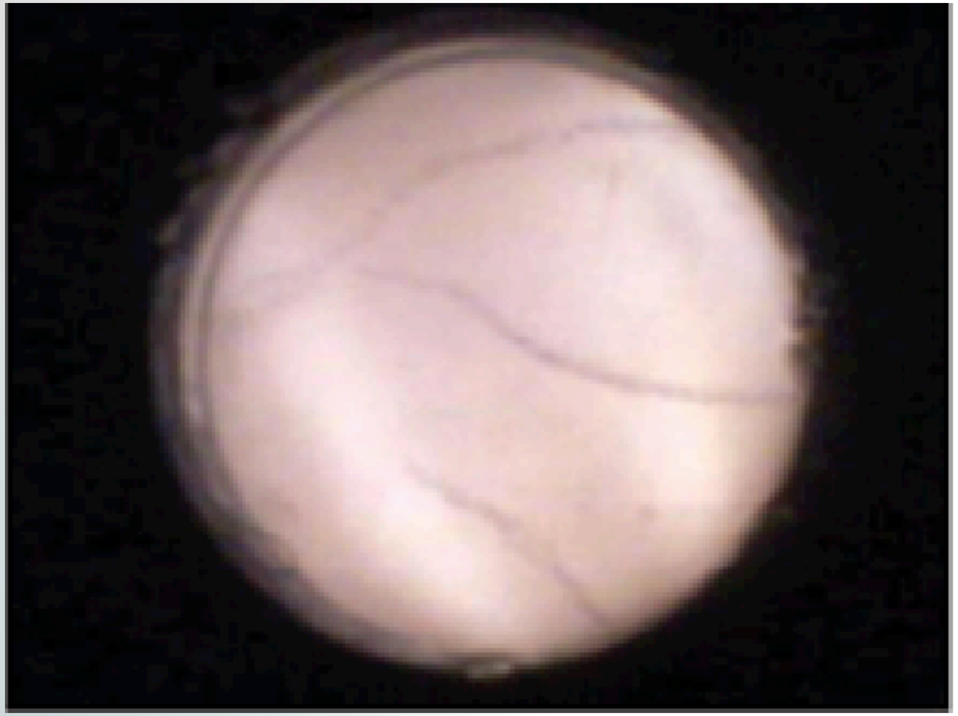


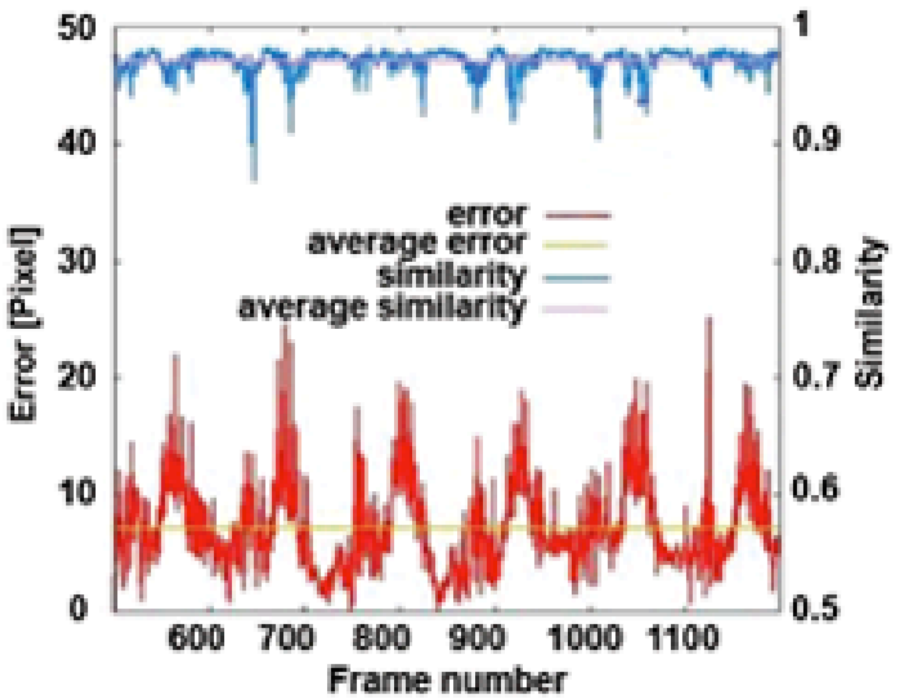


Original Image

Results: under water

Blurring

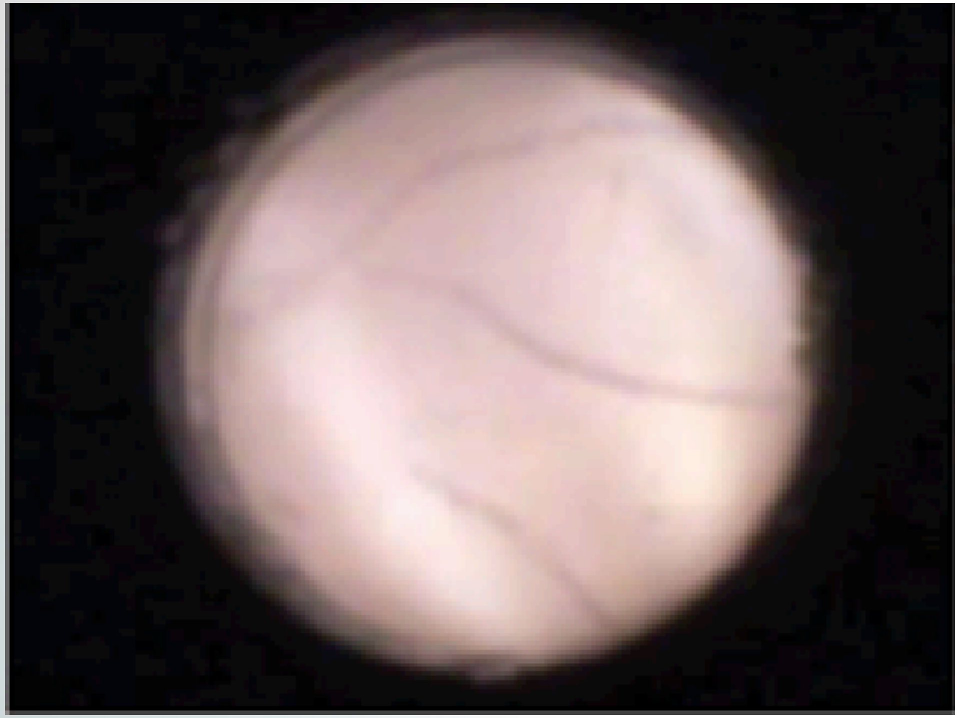


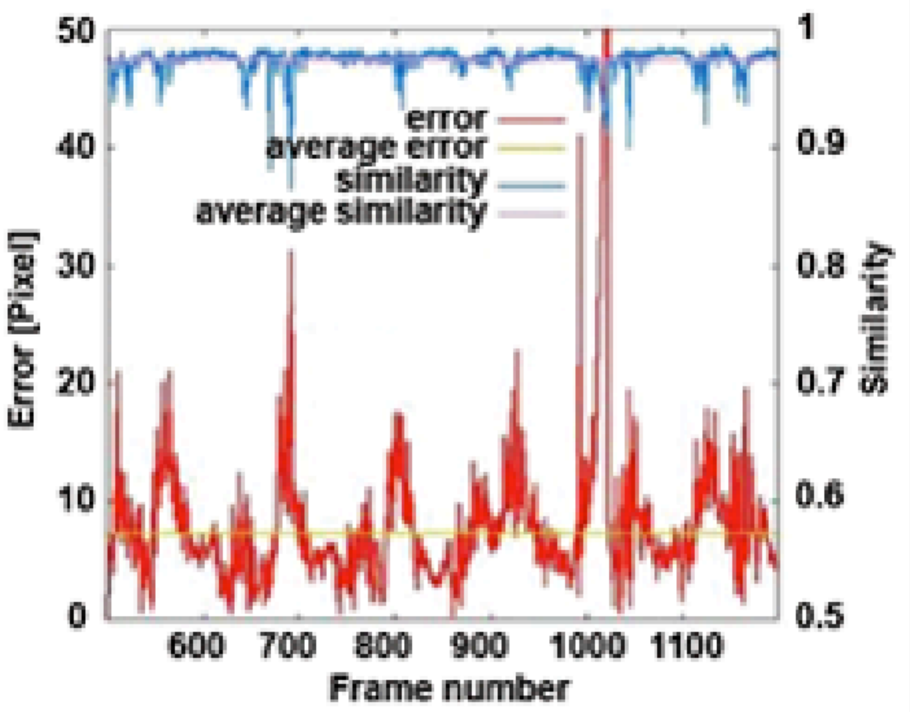


Kernel = 5

Results: under water

Blurring





Kernel = 11

Conclusions/Future Work

- FAST & LK Optical Flow
  - Detect and track feature points
  - RANSAC used to remove bad tracking
- Average errors were approximately 10 pixels
- Similarity was on average more than 0.9
- Processing Speed averaged 30 ms
- Future Work - Adjust algorithm for better handling of
  - Floating particles
  - Unobvious difference between vessel and background (pig vessel)