Advanced 7
Bio-Inspired System

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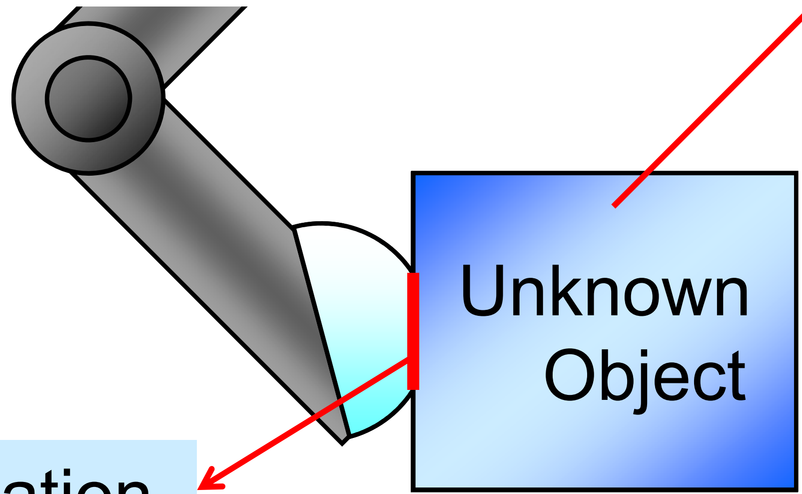
Table of Contents

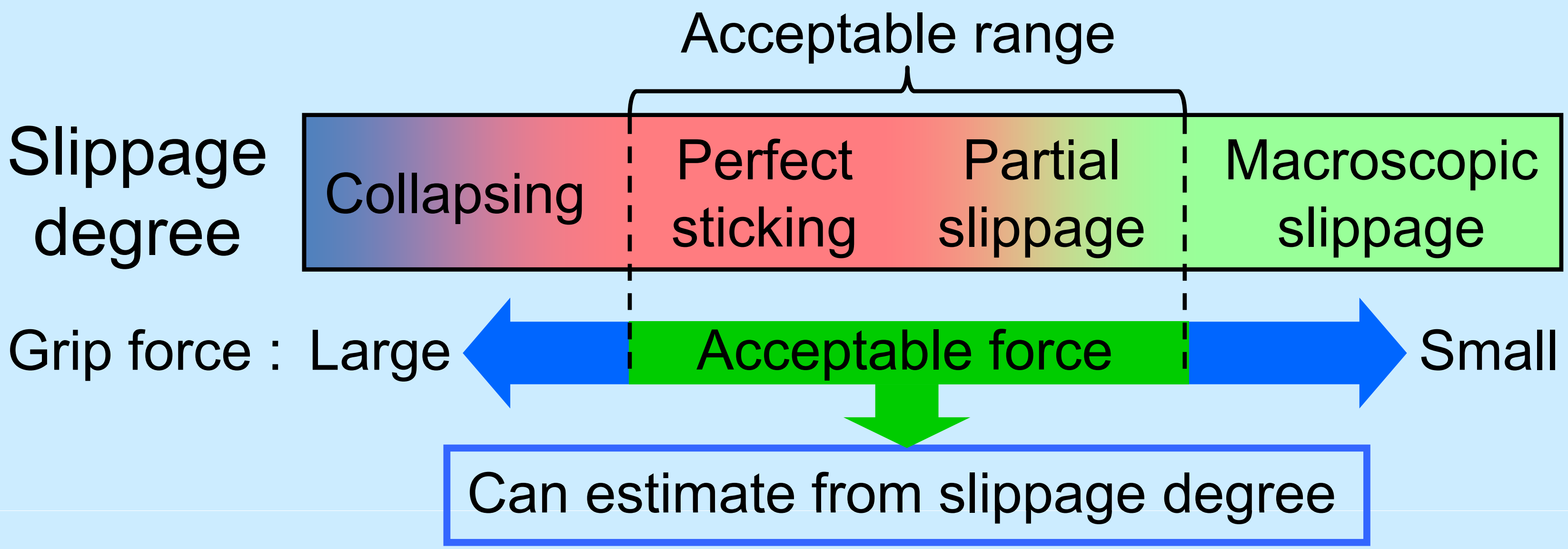
Background

Grasp of object by robot hand



<u>Unknown quantities</u>
- Weight
- Friction coefficient

<u>Tactile information</u>



Purpose

Conventional method estimates the slippage degree in simply cases.

Obinata, G., Ashis, D., Watanabe, N., and Moriyama, N. (2007). Vision Based Tactile Sensor Using Transparent Elastic Fingertip for Dexterous Handling. In Kolski, S. (ed.) *Mobile Robots: Perception & Navigation*, pp. 137-148

Extend

Estimation of slippage degree in following cases

when

- Case1
- Case2
- Case3

- sticking occurred on deformed surface
- moment is applied
- normal force is changed

Noises on images used for estimation → Reduction of accuracy

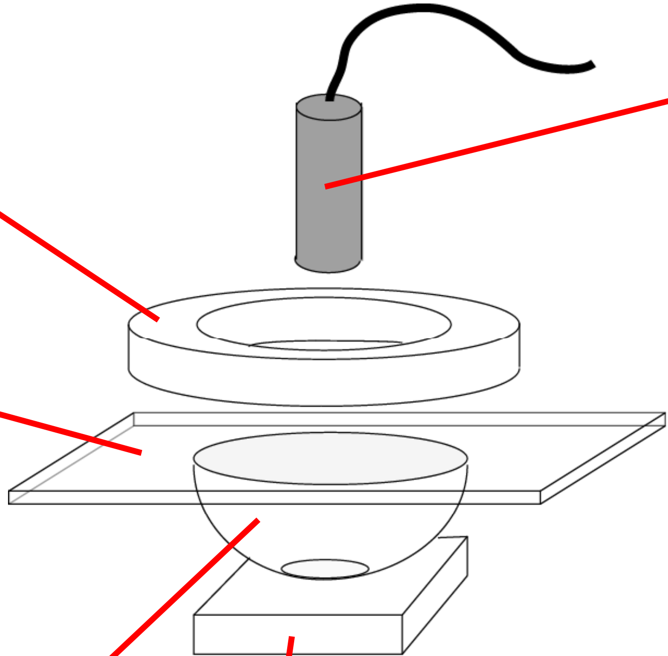
Reduction of effect of noises

Table of Contents

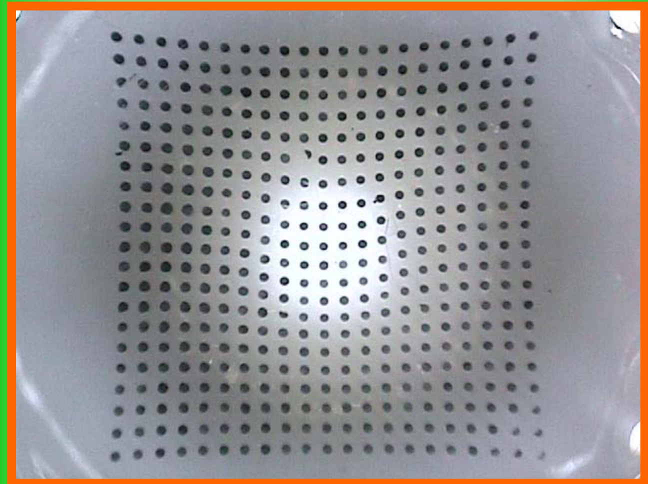
Structure of Vision-Based Tactile Sensor

LED lights

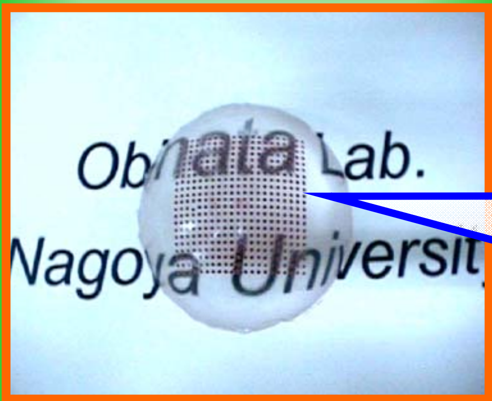
Transparent acrylic plate



CCD camera

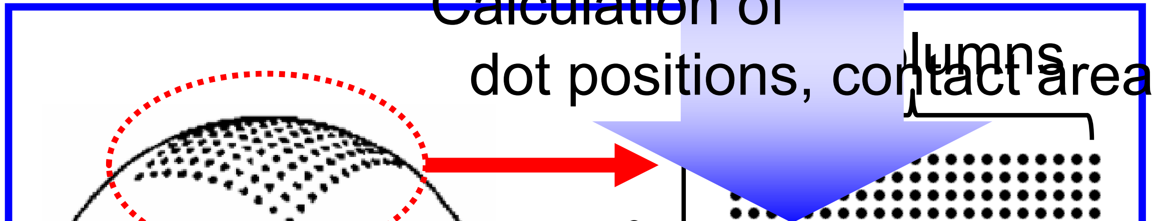


Elastic body



Object

Calculation of dot positions, contact area



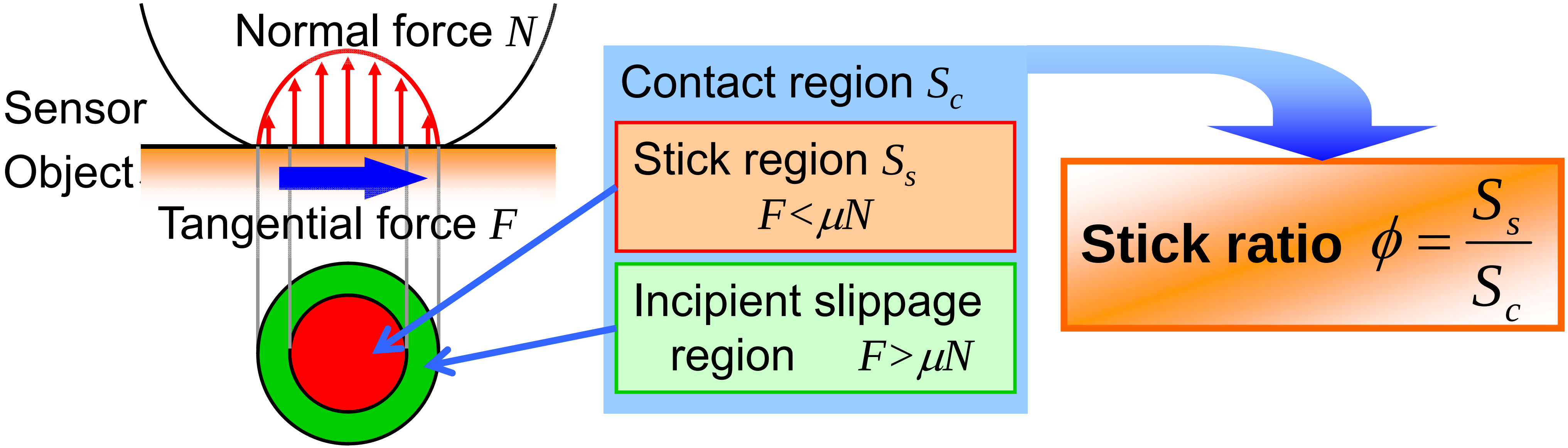
Acquisition of tactile information

- Contact force (normal, tangential, moment)
- Slippage degree

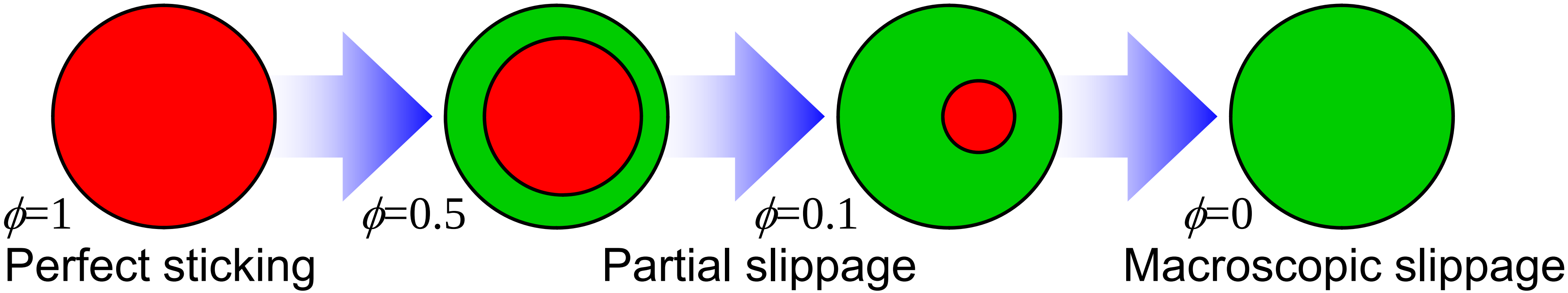
Table of Contents

Estimation of Slippage Degree

Partial slippage by non linear pressure distribution



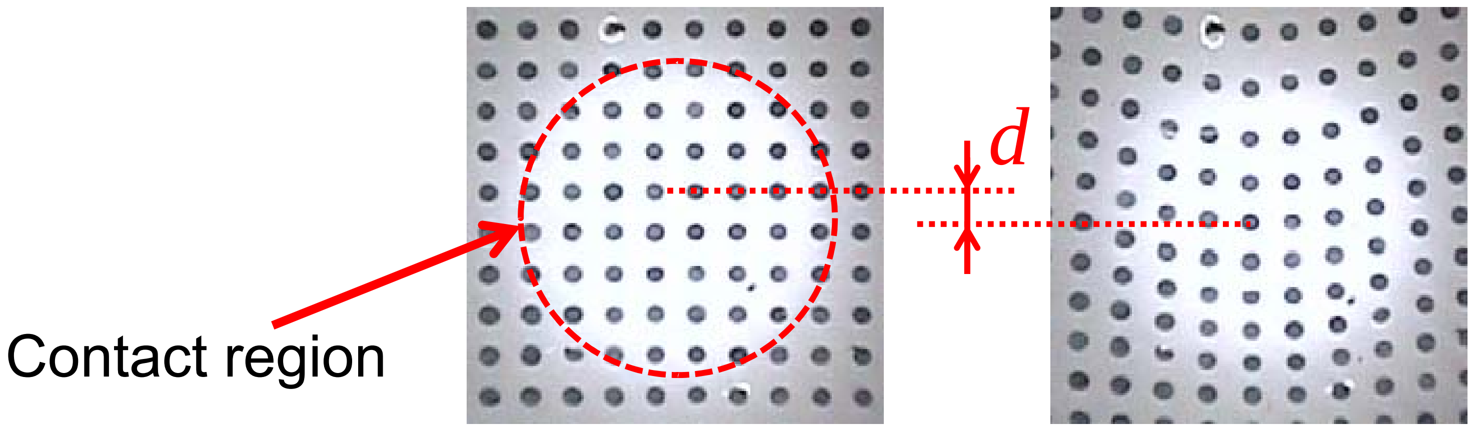
Stick ratio indicates slippage degree.



Keeping $\phi > 0$ → Preventing object from slipping

Conventional Method to Estimate Stick Ratio

Discrimination of stick/slippage region



Initial image　　Current image

Displacement

d_k : Each dot

d_0 : Central dot ≒ Object

$\lvert d_0 - d_k \rvert < \delta$	In stick region
$\lvert d_0 - d_k \rvert > \delta$	In slippage region

Estimation of ϕ with Distorted Stick Region (Case1)

The stick region is distorted.

- After the macroscopic slippage
- Change of moving direction of object
- Increase of the normal force

Reference image : STATIC → UPDATED

Initial image (static) | Current image | Updated Reference image

Reference image is selected from repository image $I_R(i)$

Current image is newly stored as the $I_R(i+1)$

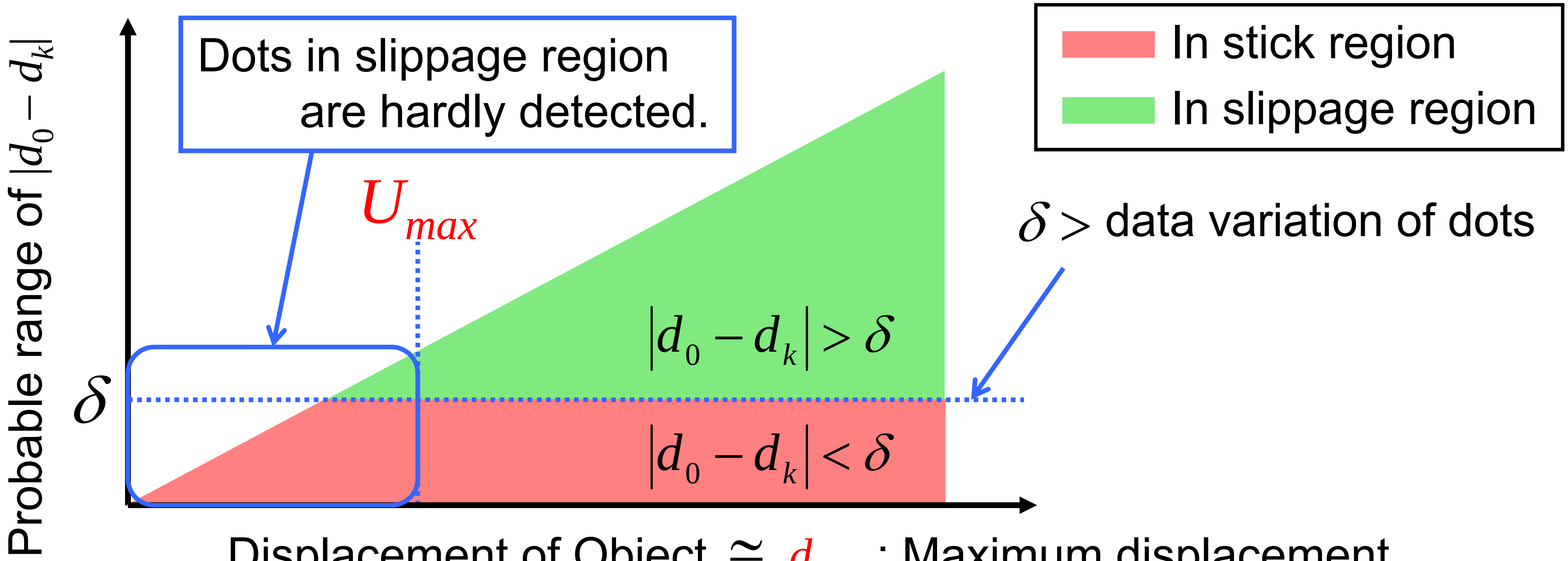
when $$d_{\max}(i) > U_{\min} \quad (i = 1,2,3,\ldots)$$

$d_{max}(i)$: Maximum displacement of dot between $I_R(i)$ and current image

U_{min} : Threshold

Estimation of ϕ with Distorted Stick Region (Case1)

First point : Required size of displacement



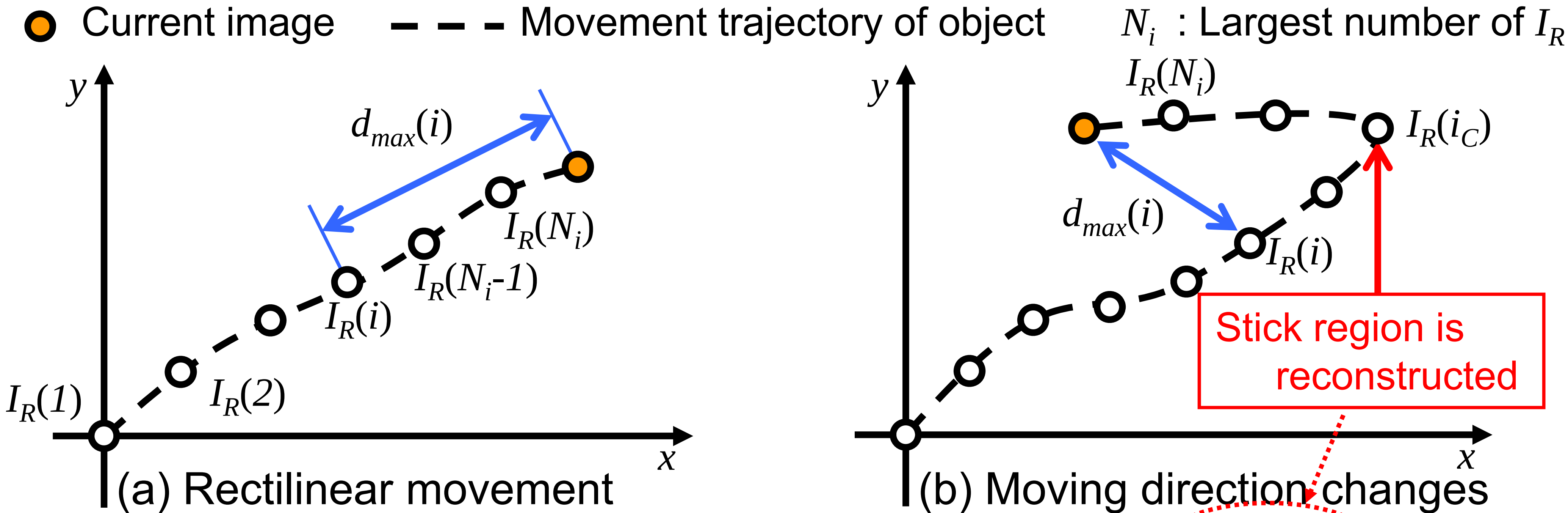
Displacement of Object $\cong$ d_{max} : Maximum displacement of dot in stick region

Reference image is selected such that $d_{\max} > U_{\max}$

$d_{max} > U_{max}$ (threshold)

Estimation of ϕ with Distorted Stick Region (Case1)

Second point : Change of moving direction



(a) Rectilinear movement

$$d_{\max}(N_i) < d_{\max}(N_i - 1) < d_{\max}(N_i - 2) < \ldots$$

(b) Moving direction changes

$$d_{\max}(N_i) < d_{\max}(N_i - 1) < \ldots < d_{\max}(i_C) > d_{\max}(i_C - 1) > \ldots$$

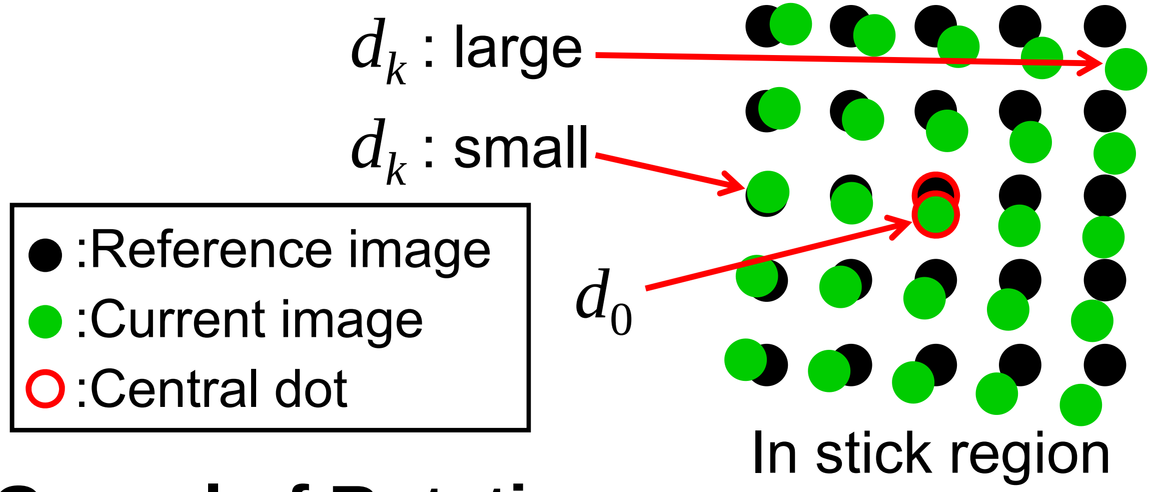
Reference image is selected such that moving direction of object doesn't change significantly during interval of two images.

Selection of reference image $I(i_{ref})$

$$i_{ref} = \sup\{ i : |d|_{\max}(i) > U_{\max}, i_C \le i \le N_i \}$$

Estimation of ϕ with Applied Moment (Case2)

Displacements in stick region are not equable.



d_0 and d_k are greatly different.

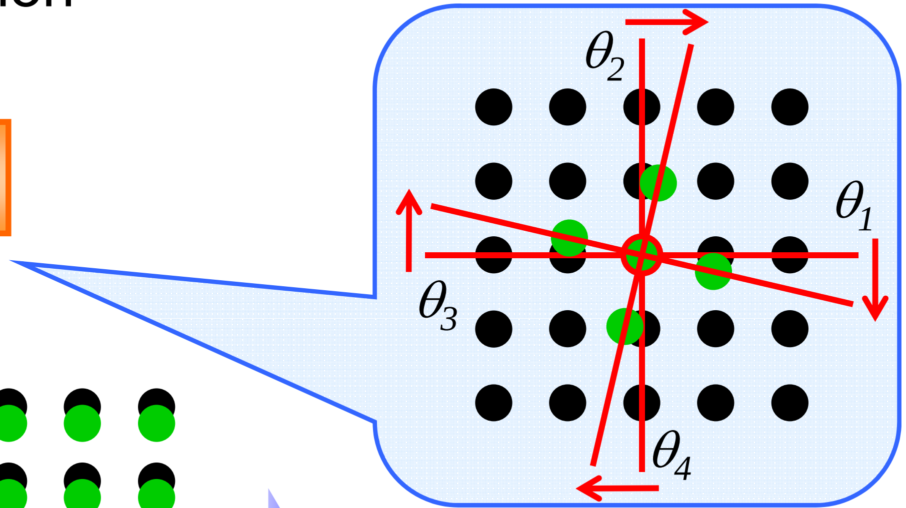
Condition in stick region

$|d_0 - d_k| < \delta$ Not satisfied

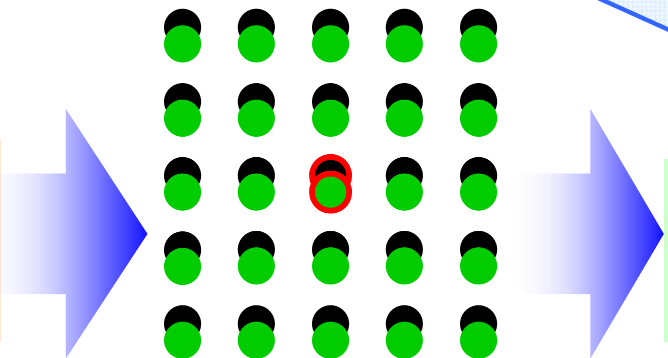
Cancel of Rotation

Estimation of Rotation angle θ_0

$$\theta_0 = \frac{\theta_1 + \theta_2 + \theta_3 + \theta_4}{4}$$



Rotation of all dots in current image



Condition in stick region

$|d_0 - d_k| < \delta$ Satisfied

Flow Chart of New Method to Estimate ϕ

Capture — Current image

Measure — Contact region, Dot positions

Canceling Rotation

Calculation — Displacements of dots between reference and current images

Second point — If $d_{max} > U$

No → (back to Capture)

Yes ↓

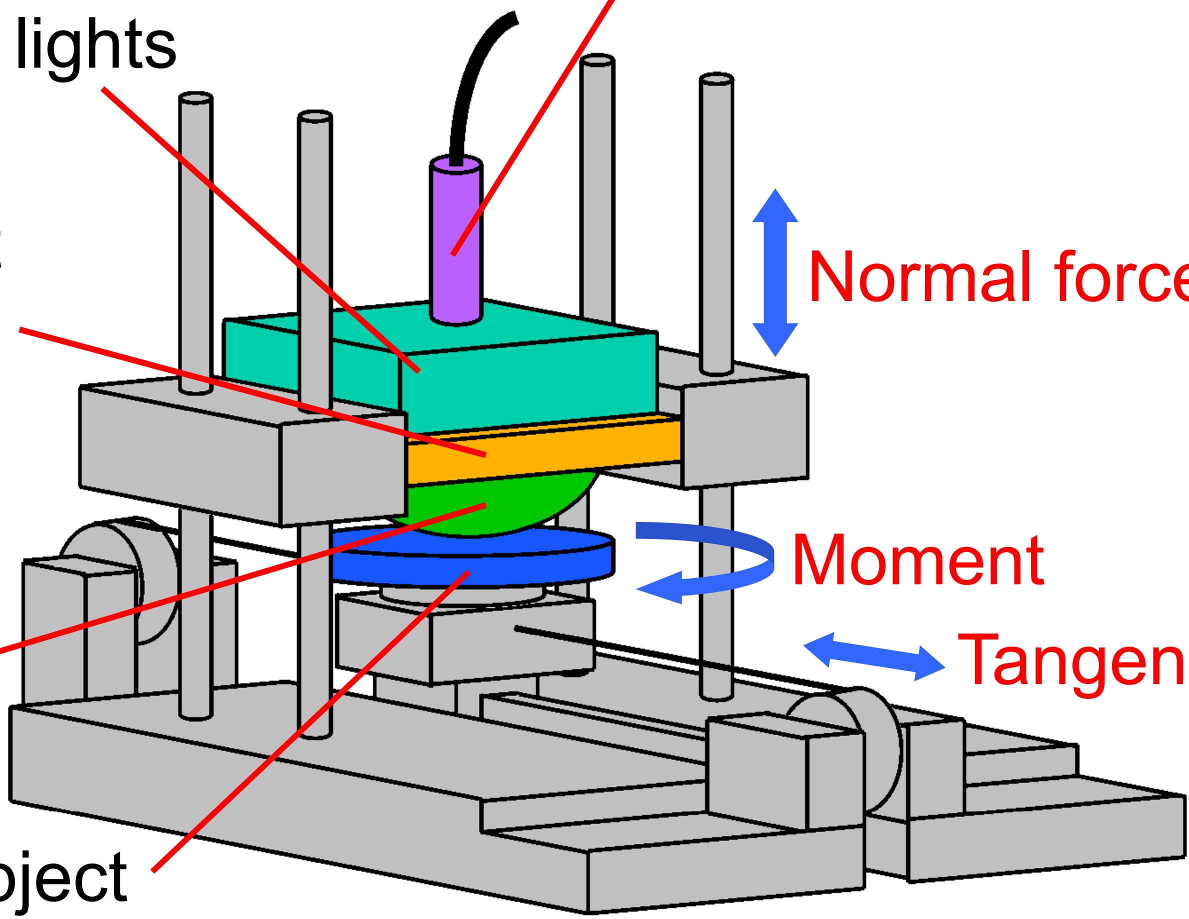
Calculation — $|d_0 - d_k| < \delta$ → $\phi = \dfrac{S_s}{S_c} = \dfrac{N_s}{N_c}$

First point — Reference image → Current image

(→ back to Capture)

Table of Contents

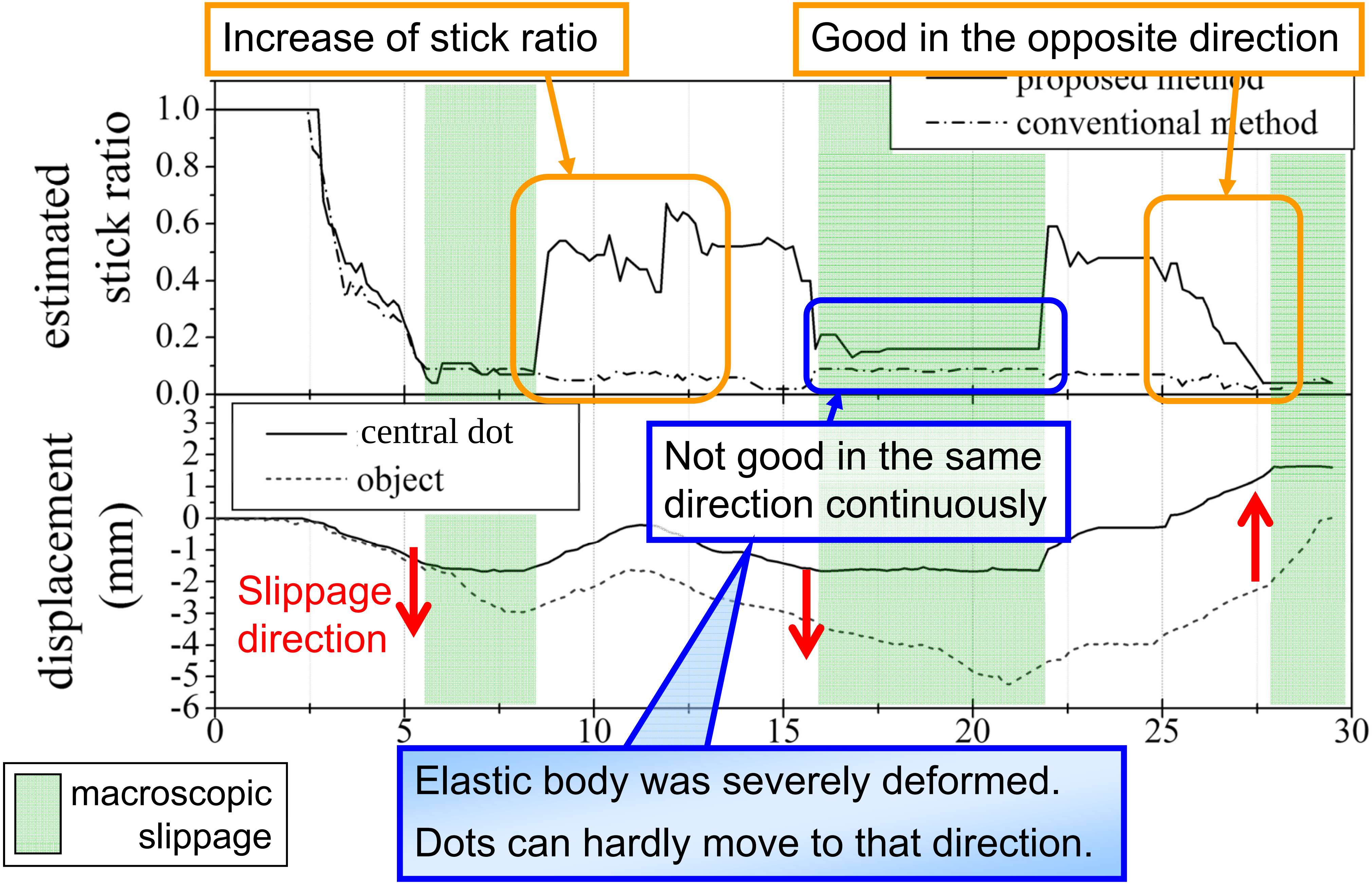
Experimental Description



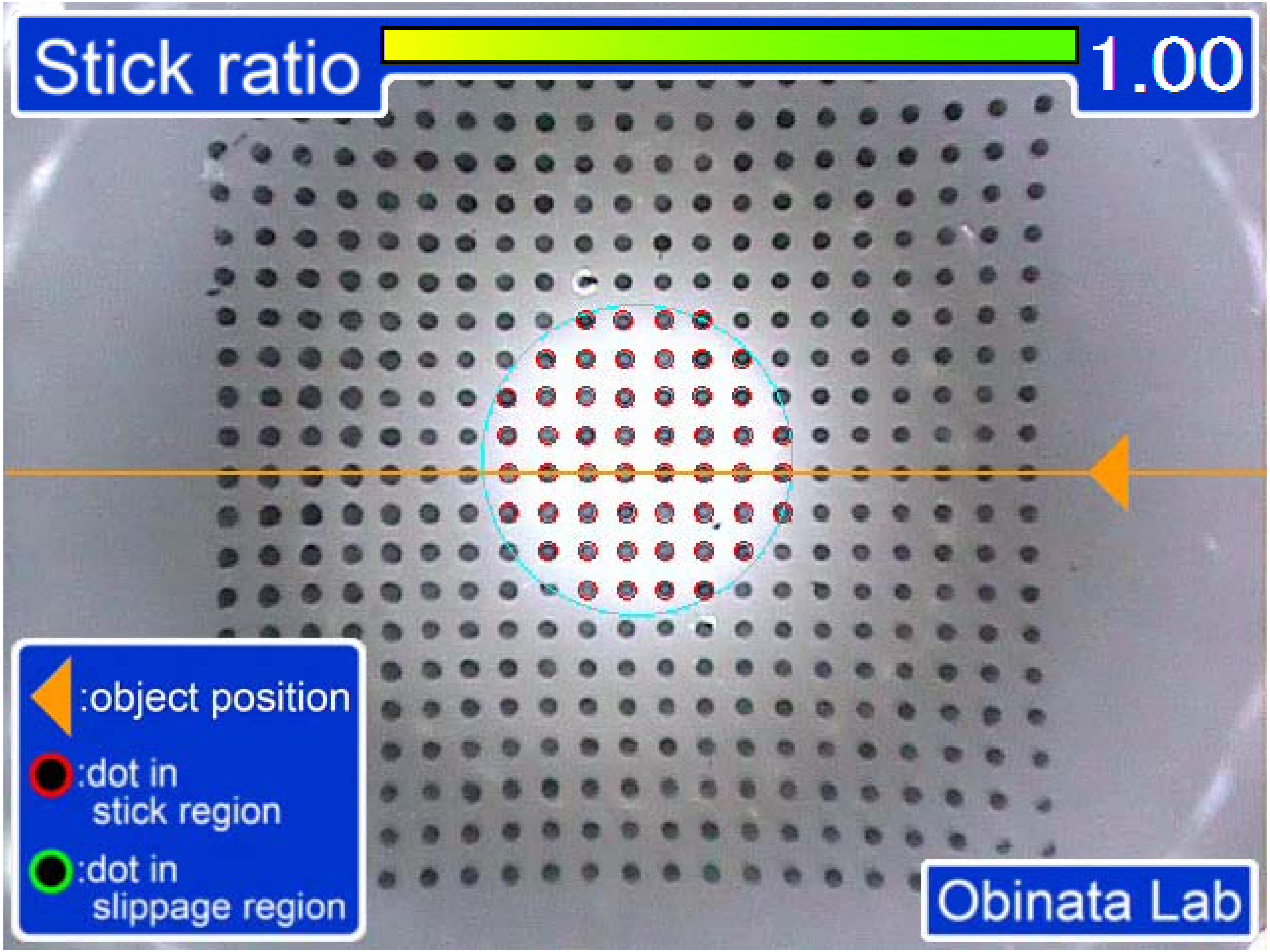
Apply
- Normal force
- Tangential force
- Moment

→ Estimation of stick ratio ϕ

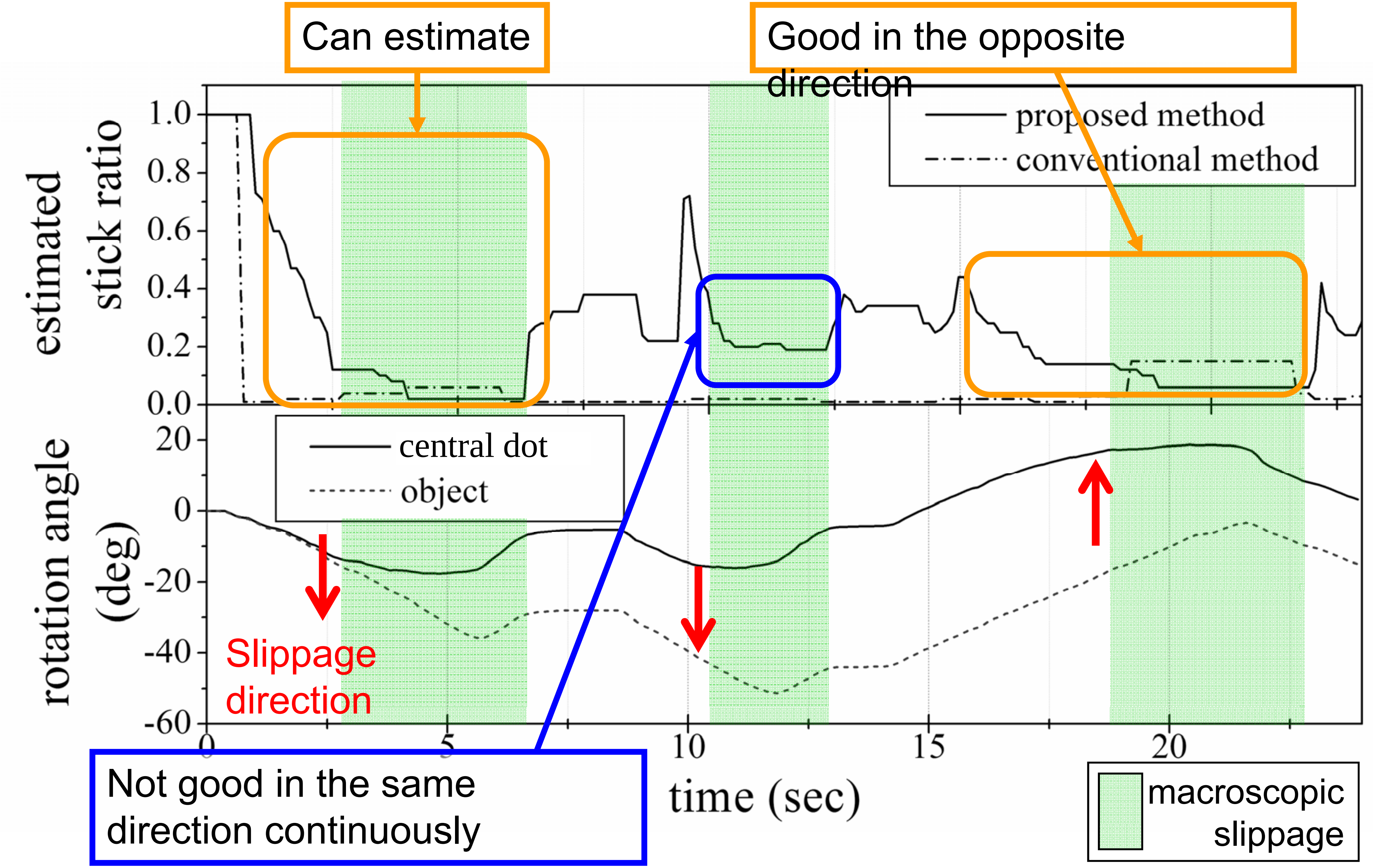
Estimation of ϕ with Distorted Stick Region (Case1)



Experimental Movie with Distorted Stick Region



Estimation of ϕ with Applied Moment (Case2)



Experimental Movie with Applied Moment

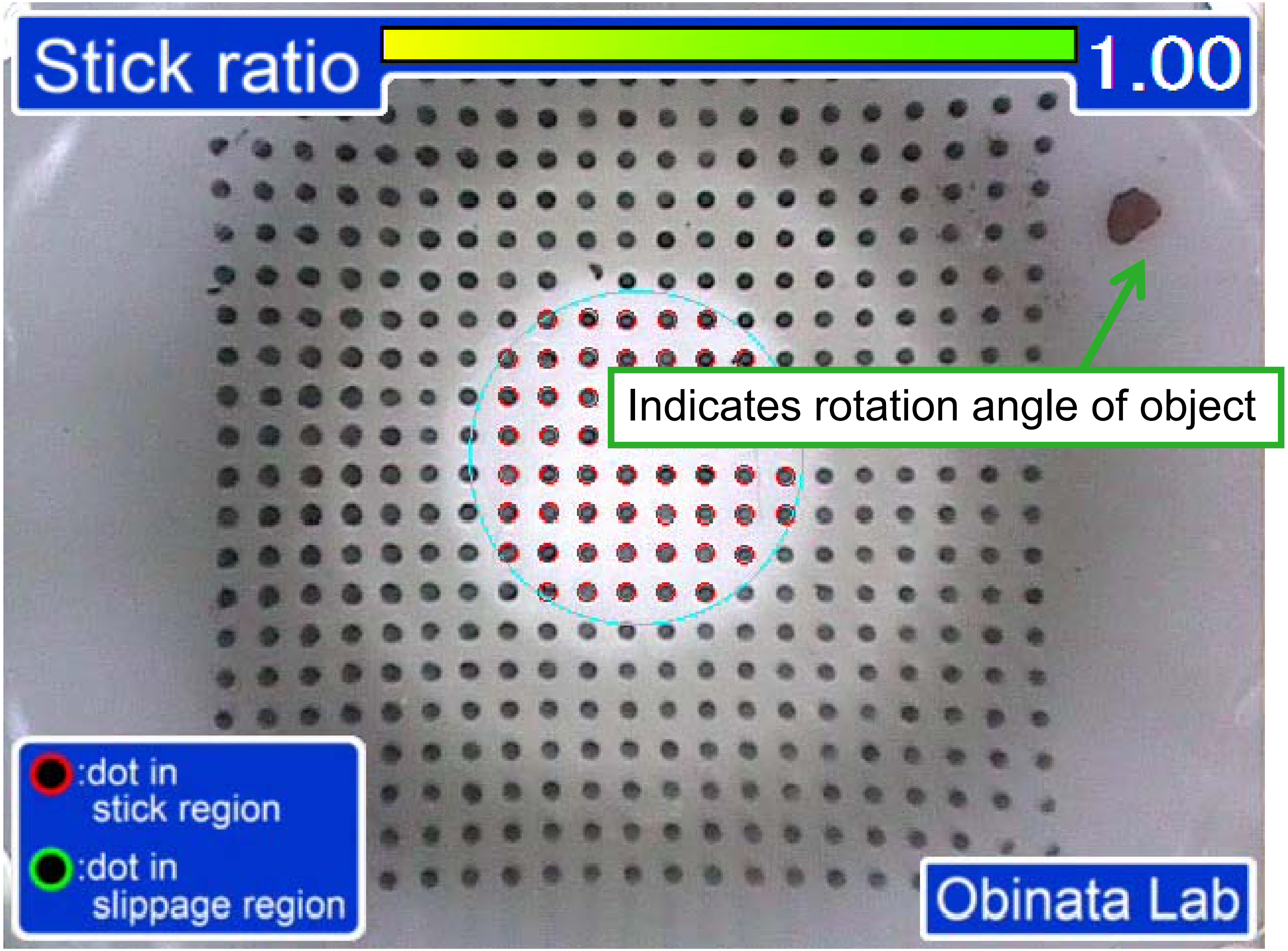


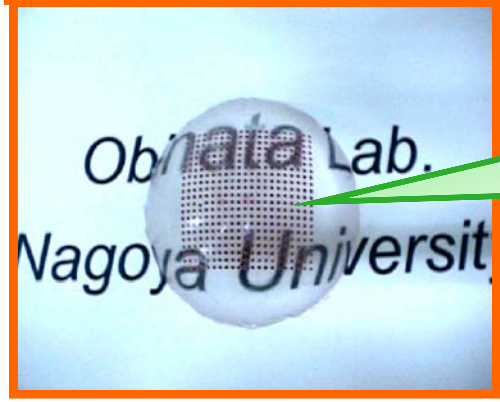
Table of Contents

Conclusion

This paper proposed …

- Estimation method of stick ratio in some major situations
- Denoising method to decrease data variation of dots

Our sensor was developed to a practical level.



Sense

- Slippage degree in many cases
- Normal force
- Tangential force
- Moment

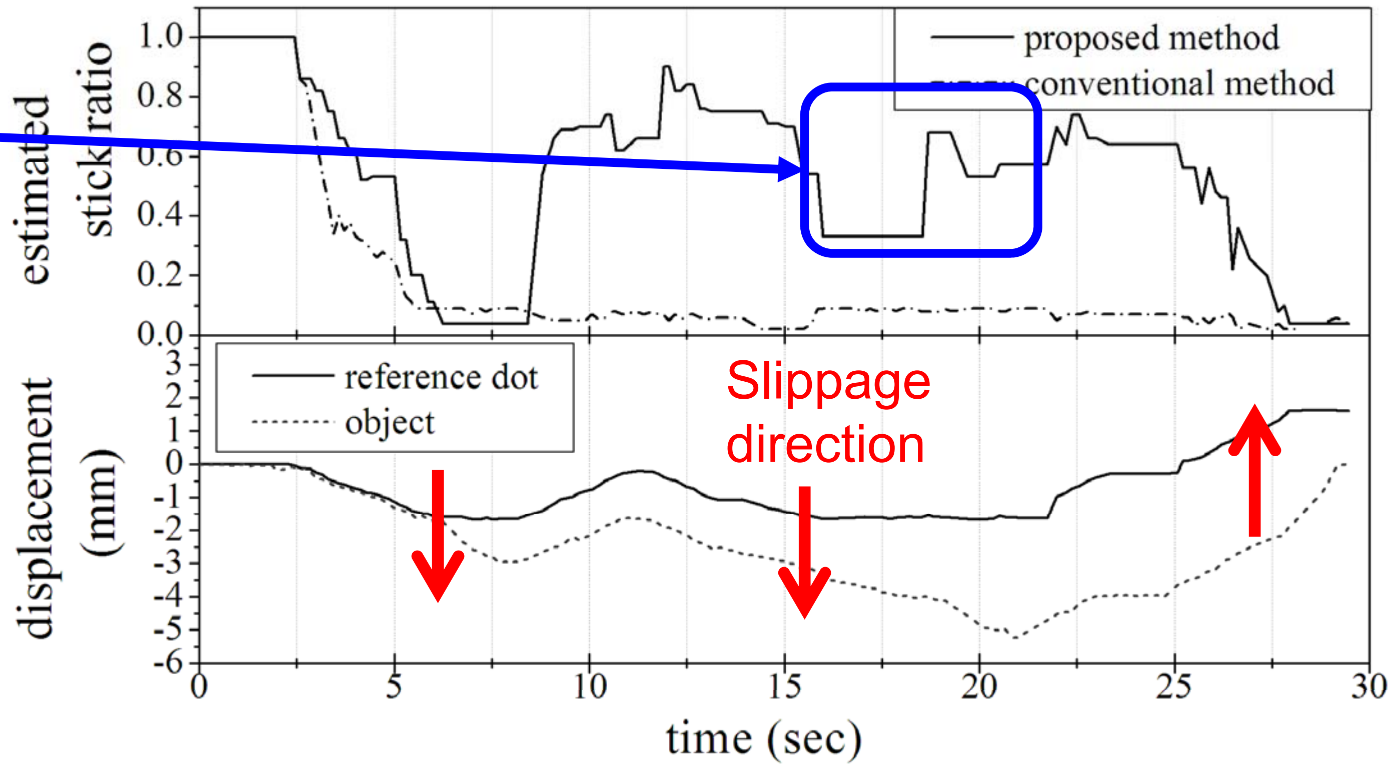
Future work

Implementation of developed sensor to robot hand to verify proposed method

Thank you for your kind attention.

Another Approach for Estimation of Slippage Degree

Not good in the same direction continuously



Another approach

When macroscopic slippage

F_0 : Tangential force

N_0 : Normal force

$\Rightarrow \mu_0 \cong \frac{F_0}{N_0}$

Current

F : Tangential force

N : Normal force

$\Rightarrow \frac{F}{N}$

Prediction of macroscopic slippage

$\frac{F}{N} < \frac{F_0}{N_0}$ ⇒ Perfect contact or partial slippage

$\frac{F}{N} \cong \frac{F_0}{N_0}$ ⇒ Macroscopic slippage

Estimation of ϕ with Normal Force Changed (Case3)

Change of normal force

Change of distance — Contact surface / CCD camera

In perspective transformation

Dots — spread toward outside. / gather toward inside.

Compensation of perspective transformation

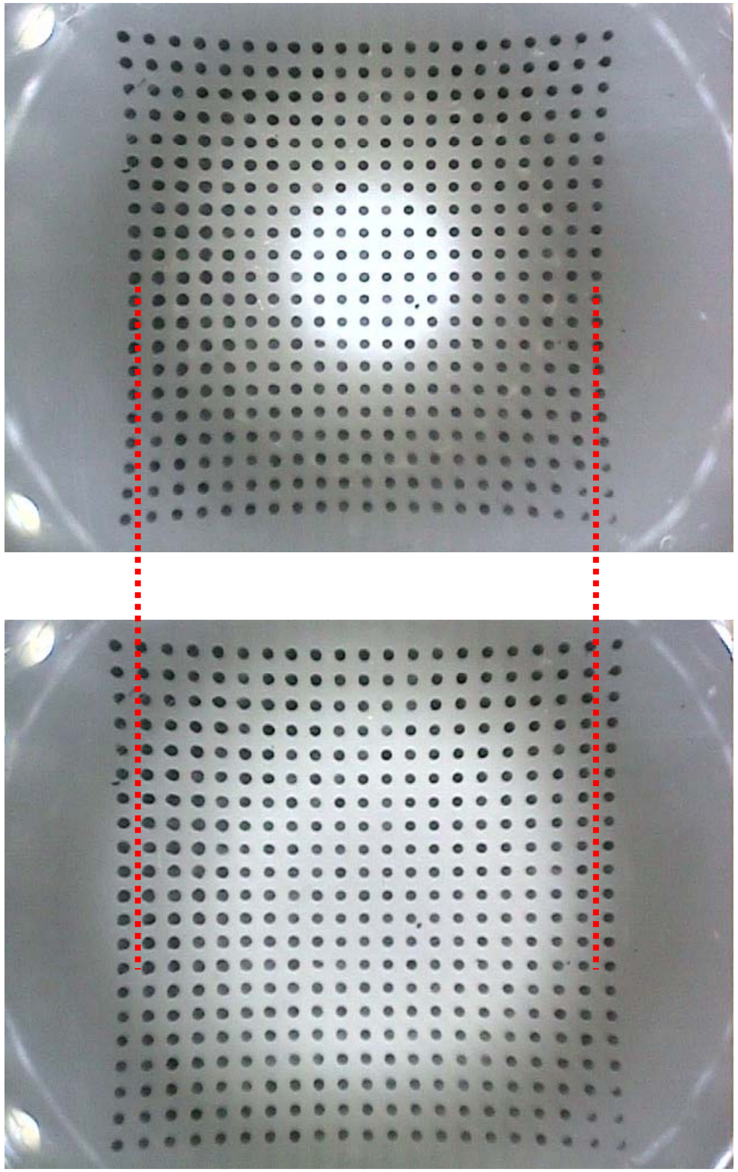
$$p_{post_k} = \alpha\left(p_{pre_k} - c\right) + c$$

α : Scale parameter between two images

c : Central position of image

p_{pre} : dot position before compensation

p_{post} : dot position after compensation



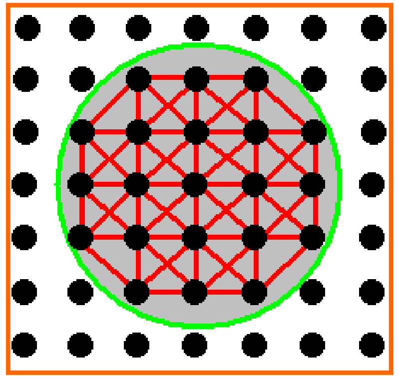
Increase of normal force

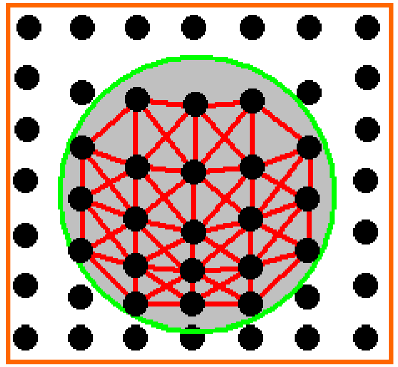
Calculation of Scale Parameter α

Sum of all distances of adjacent two dots in contact region

Comparing

$$\alpha = \frac{\sum_{(x,y)=(-1,1),(0,1),(1,1),(1,0)} \sum_{k,l} \left| p_{ref\,k,l} - p_{ref\,k+x,l+y} \right|}{\sum_{(x,y)=(-1,1),(0,1),(1,1),(1,0)} \sum_{k,l} \left| p_{cur\,k,l} - p_{cur\,k+x,l+y} \right|} \begin{array}{l} \text{Reference image} \\ \text{Current image} \end{array}$$



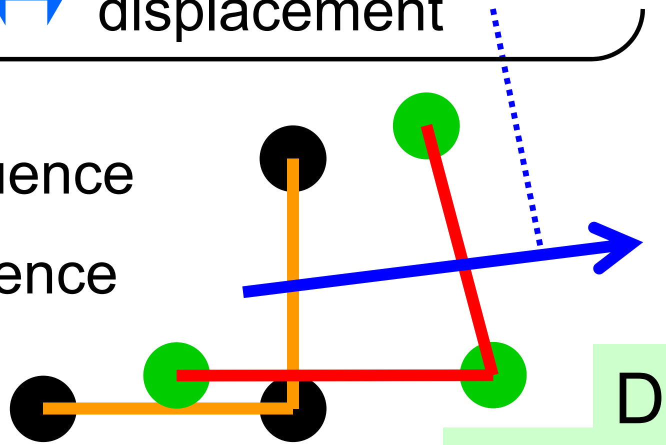


Influence by deformation of contact region

Line segment between two dots ⟺ Average direction of displacement

Parallel : High-influence

Vertical : Low-influence



Elimination of parallel component

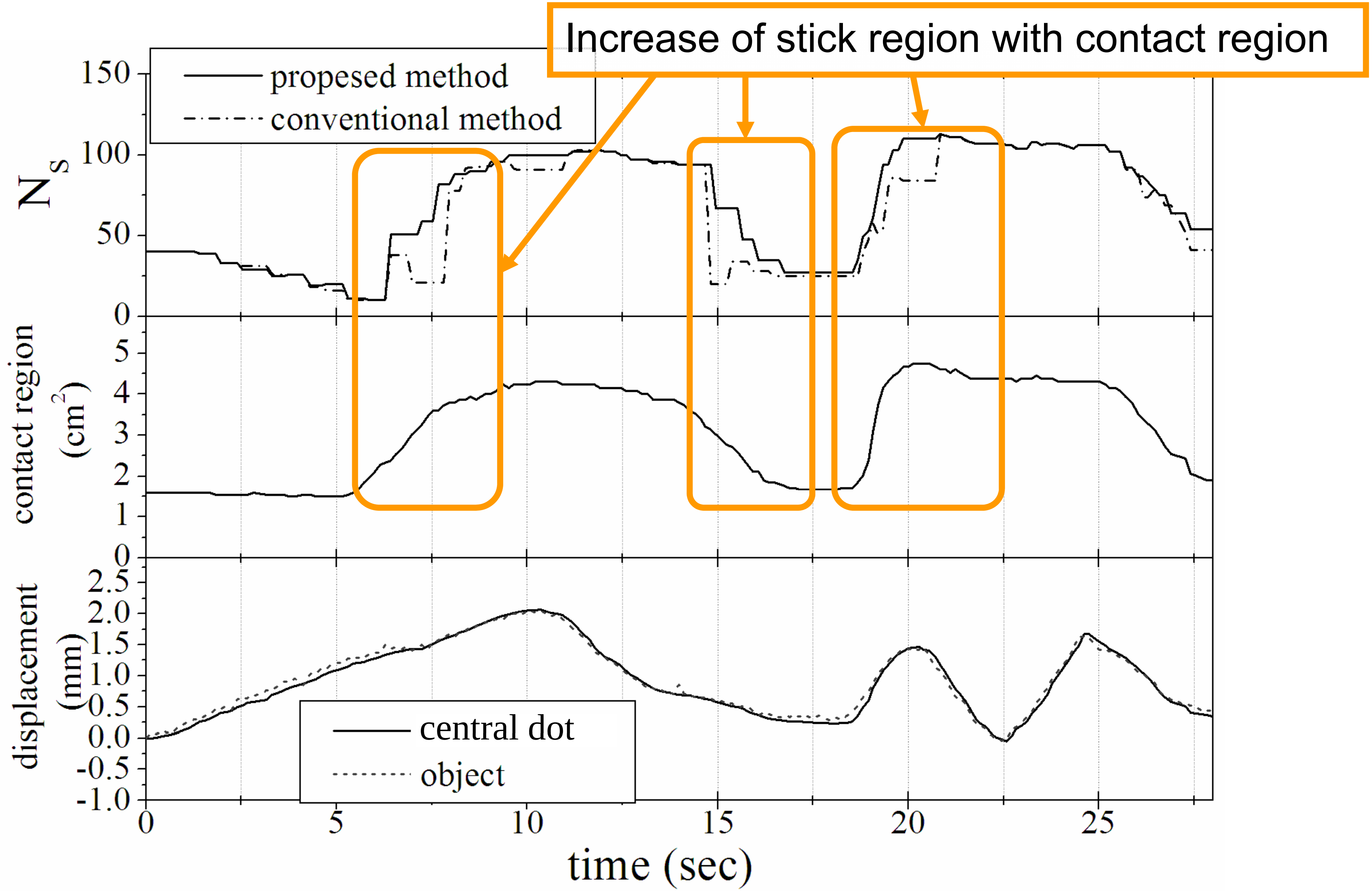
Decrease of influence

$$\alpha = \frac{\sum_{(x,y)=(-1,1),(0,1),(1,1),(1,0)} \sum_{k,l} \left| \left(p_{ref\,k,l} - p_{ref\,k+x,l+y} \right) \times q_{x,y} \right|}{\sum_{(x,y)=(-1,1),(0,1),(1,1),(1,0)} \sum_{k,l} \left| \left(p_{cur\,k,l} - p_{cur\,k+x,l+y} \right) \times q_{x,y} \right|}$$

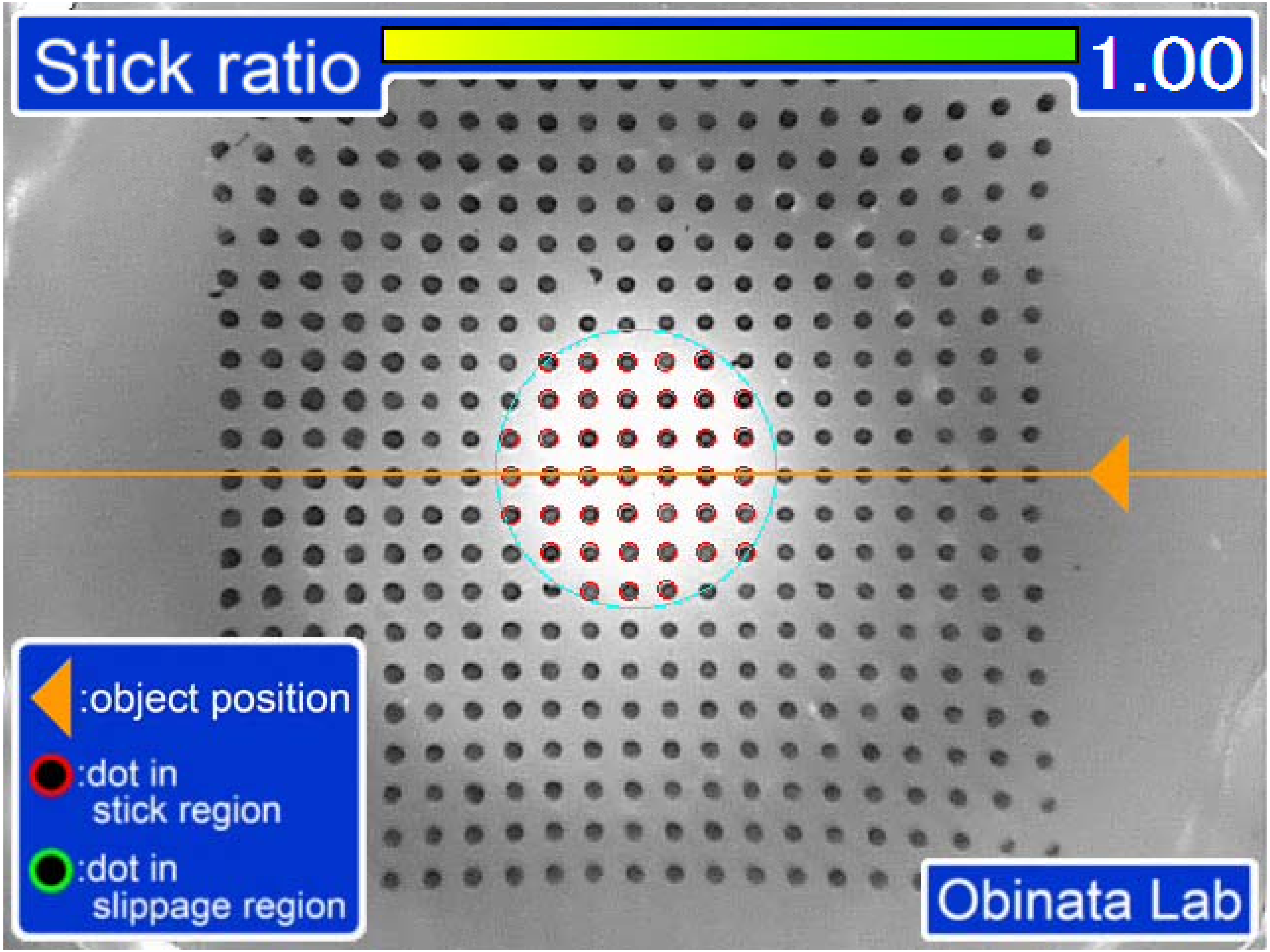
Unit vector of displacement direction

$$q_{x,y} = \frac{\left(p_{cur\,k,l} - p_{ref\,k,l} \right) + \left(p_{cur\,k+x,l+y} - p_{ref\,k+x,l+y} \right)}{\left| \left(p_{cur\,k,l} - p_{ref\,k,l} \right) + \left(p_{cur\,k+x,l+y} - p_{ref\,k+x,l+y} \right) \right|}$$

Estimation of ϕ with Normal Force Changed (Case3)



Experimental Movie with a Normal Force Changed



Reference dot

$$\left| d_0 - d_k \right| < \delta$$

Displacement of central dot

Displacement of reference dot

Reference dot：the nearest dot from the center of the stick region

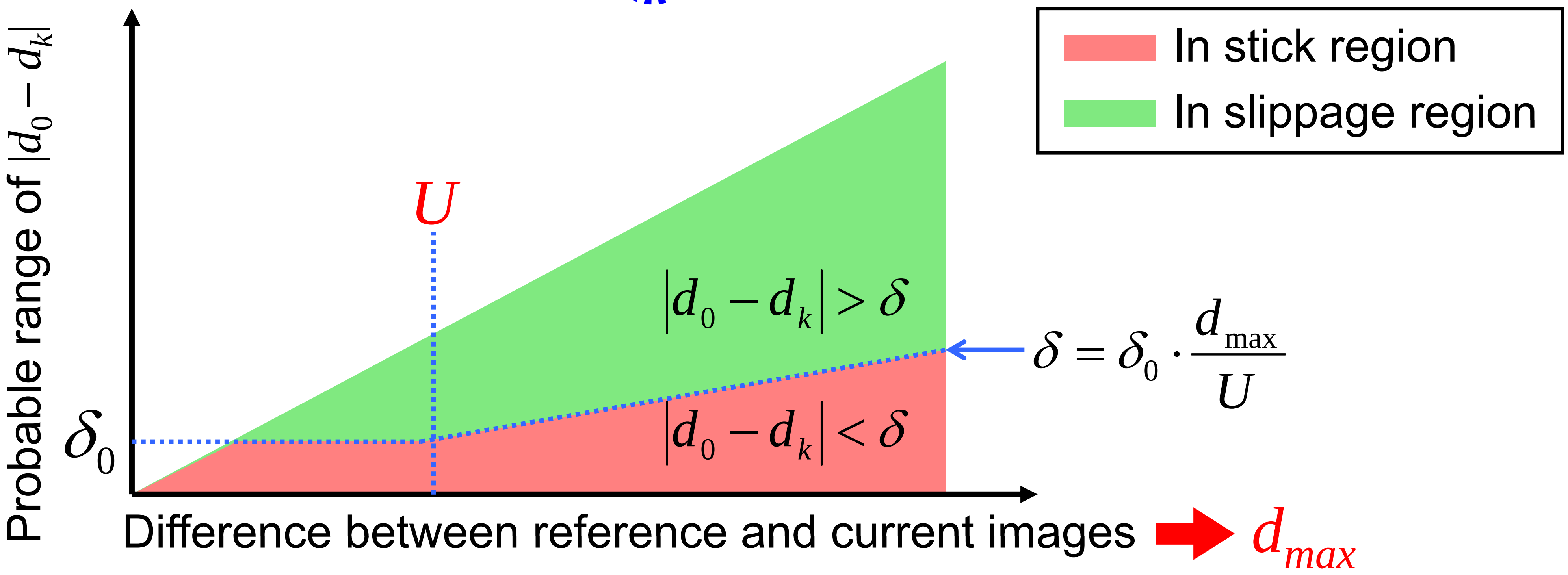
- The central dot is not always in the stick region.
- Since the reference dot moves along the stick region movement, we easily obtain the stick ratio even when the contact surface is moving.

Detail of δ

$d_{\max} > U$ → $d_{\max} \neq U$

In order to discriminate stick and slippage regions **in stable sensitivity**, d_{max} should be considered to define δ.

$$\left| d_0 - d_k \right| < \delta = \delta_0 \frac{d_{\max}}{U}$$



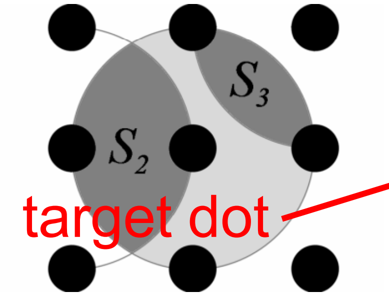
Method to decrease of data variation of dots

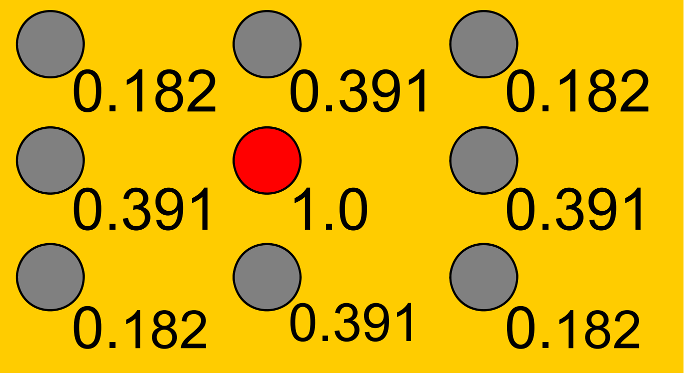
Variations in the dot positions from noises

→ weighted average of target dot and the adjacent 8 dots

$$p_{post_{k,l}} = \begin{cases} \dfrac{\sum_{m=k-1}^{k+1}\sum_{n=l-1}^{l+1} w_{m,n} p_{pre_{m,n}}}{\sum_{m=k-1}^{k+1}\sum_{n=l-1}^{l+1} w_{m,n}} & (k \neq 1,21 \quad and \quad l \neq 1,21) \\ p_{pre_{k,l}} & (k = 1,21 \quad or \quad l = 1,21) \end{cases}$$

$$\begin{Bmatrix} w_{k-1,l-1} & w_{k,l-1} & w_{k+1,l-1} \\ w_{k-1,l} & w_{k,l} & w_{k+1,l} \\ w_{k-1,l+1} & w_{k,l+1} & w_{k+1,l+1} \end{Bmatrix} = \begin{Bmatrix} S_3 & S_2 & S_3 \\ S_2 & S_1 & S_2 \\ S_3 & S_2 & S_3 \end{Bmatrix}$$



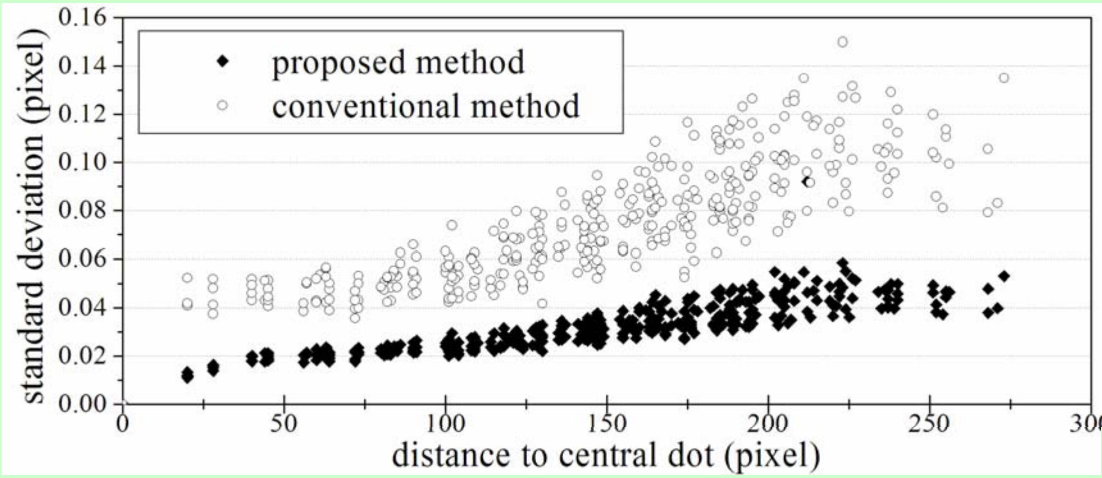


Experimental Results

Standard deviation σ of relative dot position in reference to central dot

Maximum

0.14 pixel → 0.06 pixel



Selection of δ_0

- δ_0 is small. → The sensitivity of ϕ estimation is good.
- δ_0 > dot variations → To minimize the effect of the dot variations

Regardless reference dot…

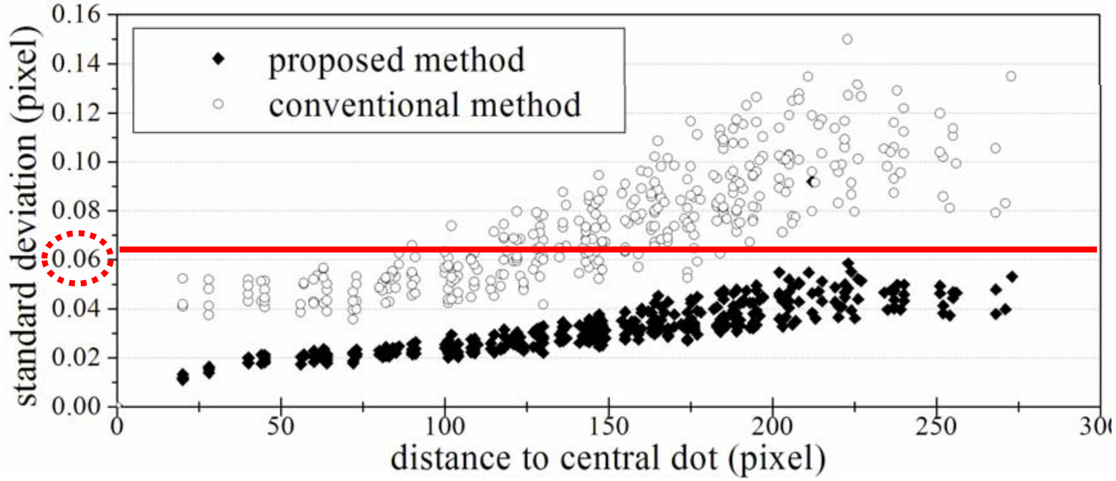
standard deviation σ < 0.06 pixel

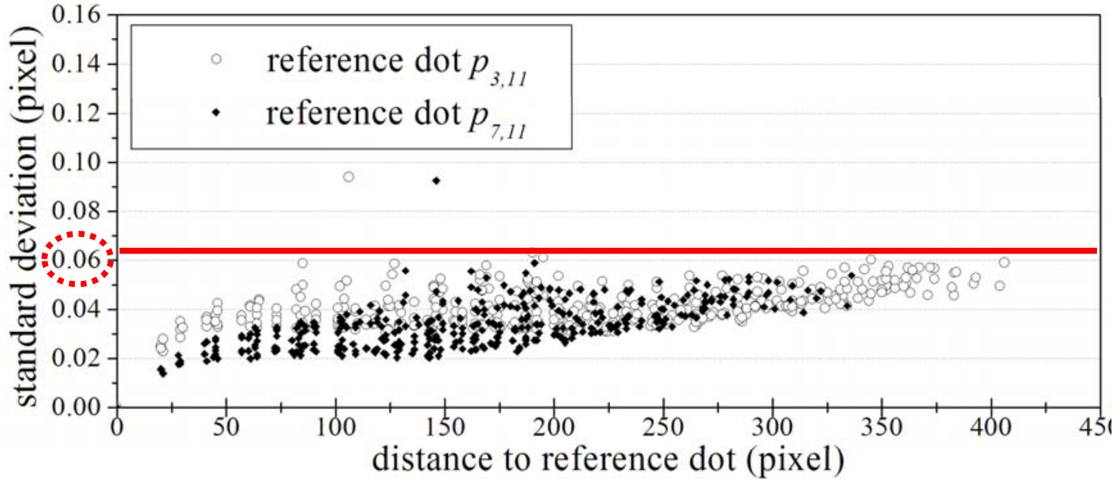
σ_{max} = 0.06 pixel

95.44%

Relative displacement < 0.24 pixel ($\pm 2\ \sigma_{max}$)

$$\delta_0 = 4\sigma_{max} = 0.24 \text{ pixel}$$





Selection of U

Two measures for U

n_s : the step number (58)

$$S = \sum_{i=1}^{n_s} \phi_i$$

The earlier the decrease of ϕ is, the smaller S is.

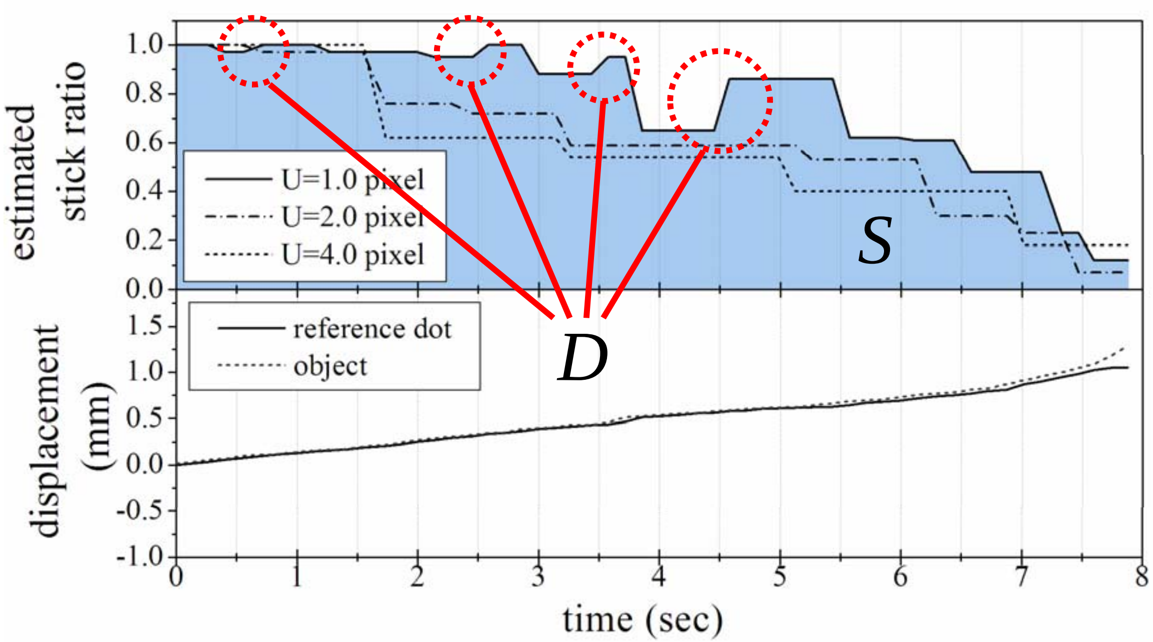
$$D = \sum_{i=2}^{n_s} \Delta\phi_i \qquad \Delta\phi = \begin{cases} \phi_{i-1} - \phi_i & (\phi_i < \phi_{i-1}) \\ 0 & (\phi_i \geq \phi_{i-1}) \end{cases}$$

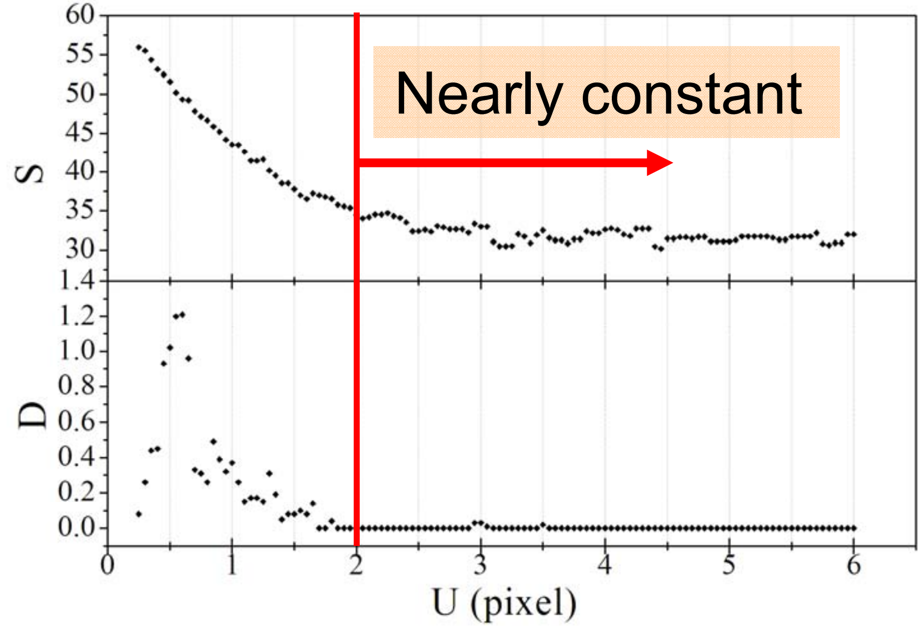
Regarded as the level of estimation error

Fast response of *f* estimation

→ U should be small.

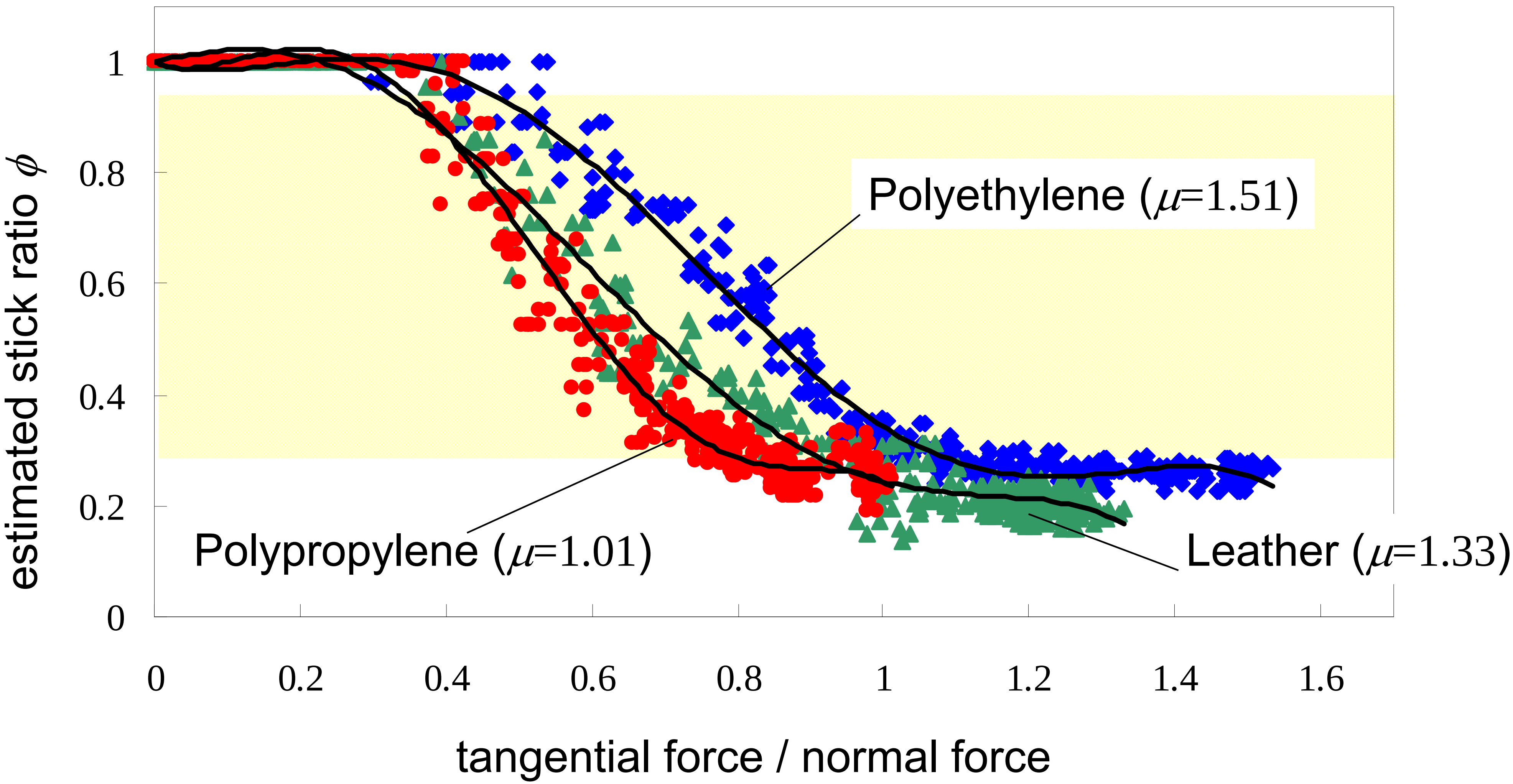
Desirable → U, S and D are small.





U = 2.0 pixel

Estimation of Friction Coefficient

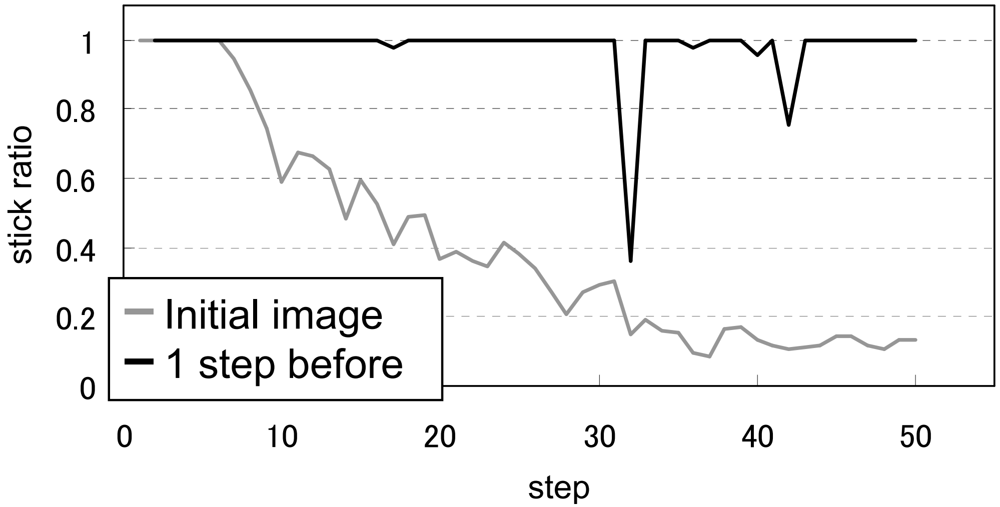


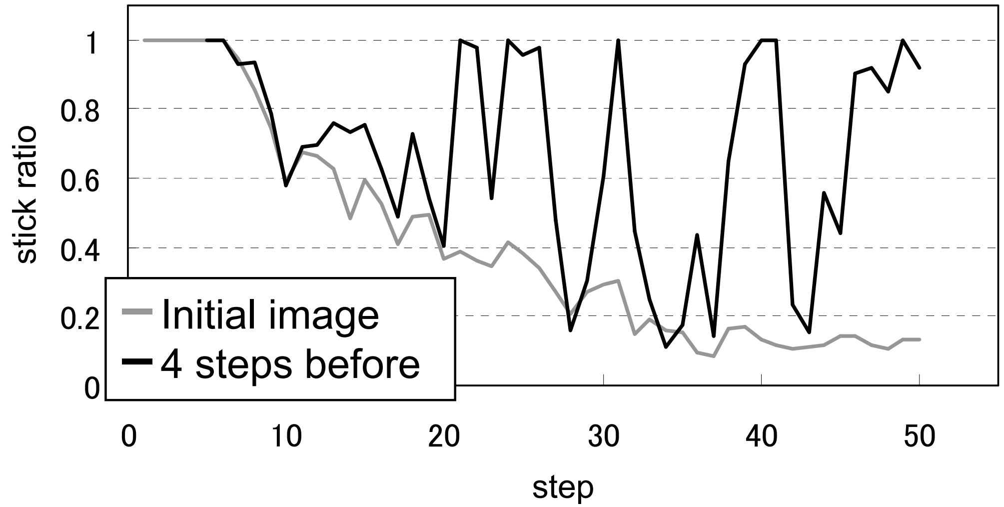
Stick ratio to ratio between two forces → Estimation? → Friction coefficient

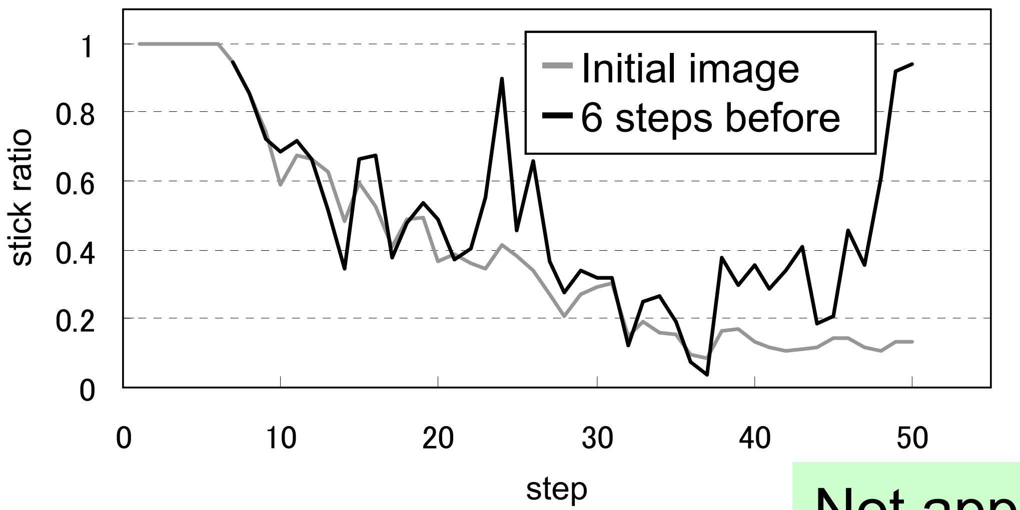
Example of Application of Reference Image

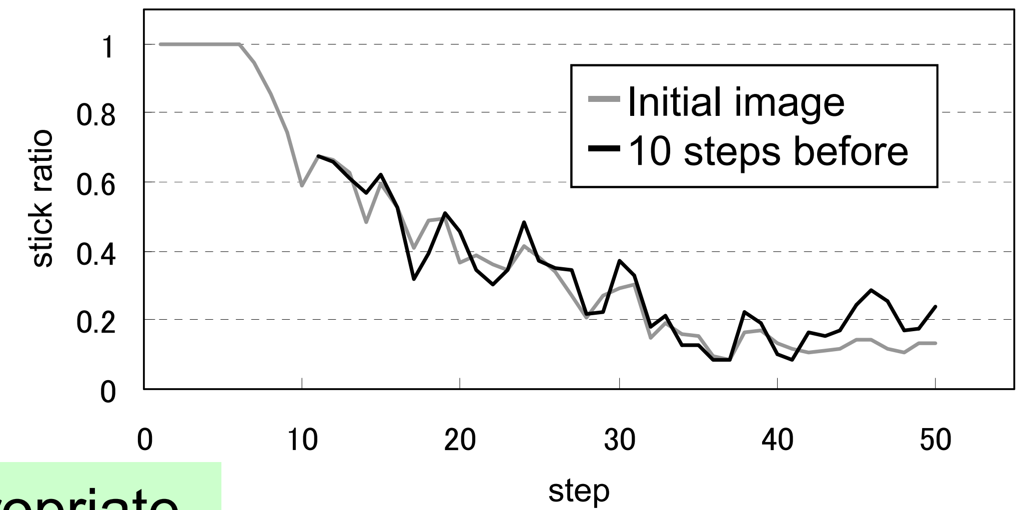
Second point

the image captured several steps before → Reference image





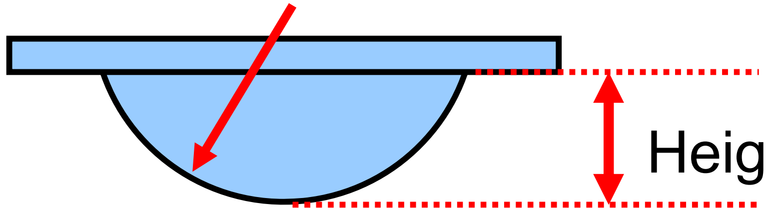




Not appropriate

Forecasted Question

Size of sensor



Equation of Rotation

$$p_{post_k} = \begin{bmatrix} \cos\theta_0 & \sin\theta_0 \\ -\sin\theta_0 & \cos\theta_0 \end{bmatrix} \left(p_{pre_k} - p_{pre_0} \right) + p_{pre_0}$$

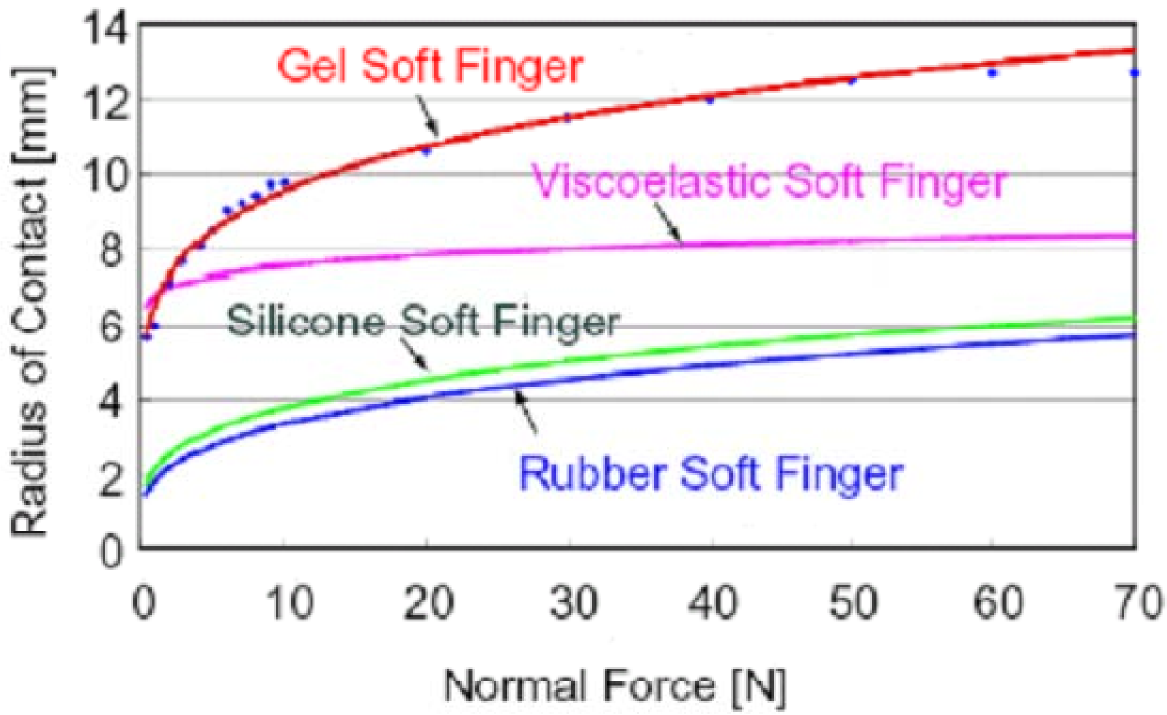
p_k: Each dot position
p_0: Central dot position
pre: Before rotation
$post$: After rotation

Processing speed

The processing speed depends on spec of PC.
Currently, the processing speed about 4Hz.

Forecasted Question

Selection of material

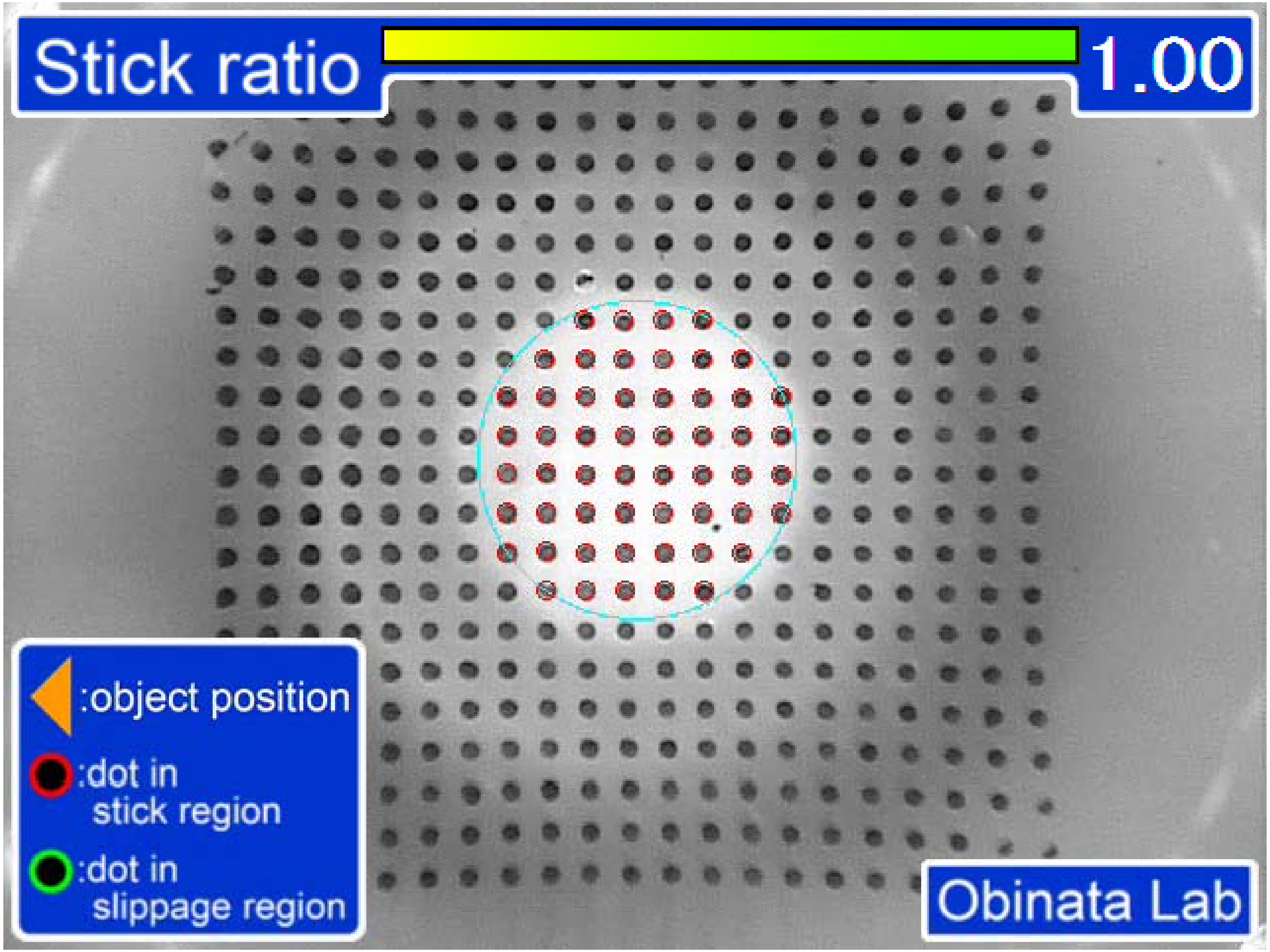


Selection points

- Hard (for measure of contact force in wide range)
- Transparent (for capture of image from reverse side)
- Flexible (for increase of moving range of dots)

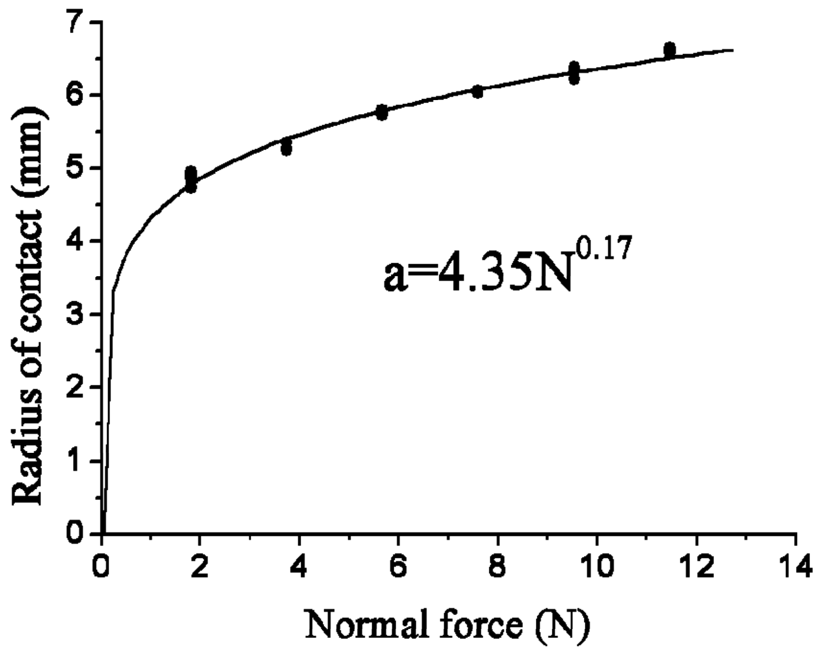
Silicon rubber

Experimental Movie with Forces and a Moment

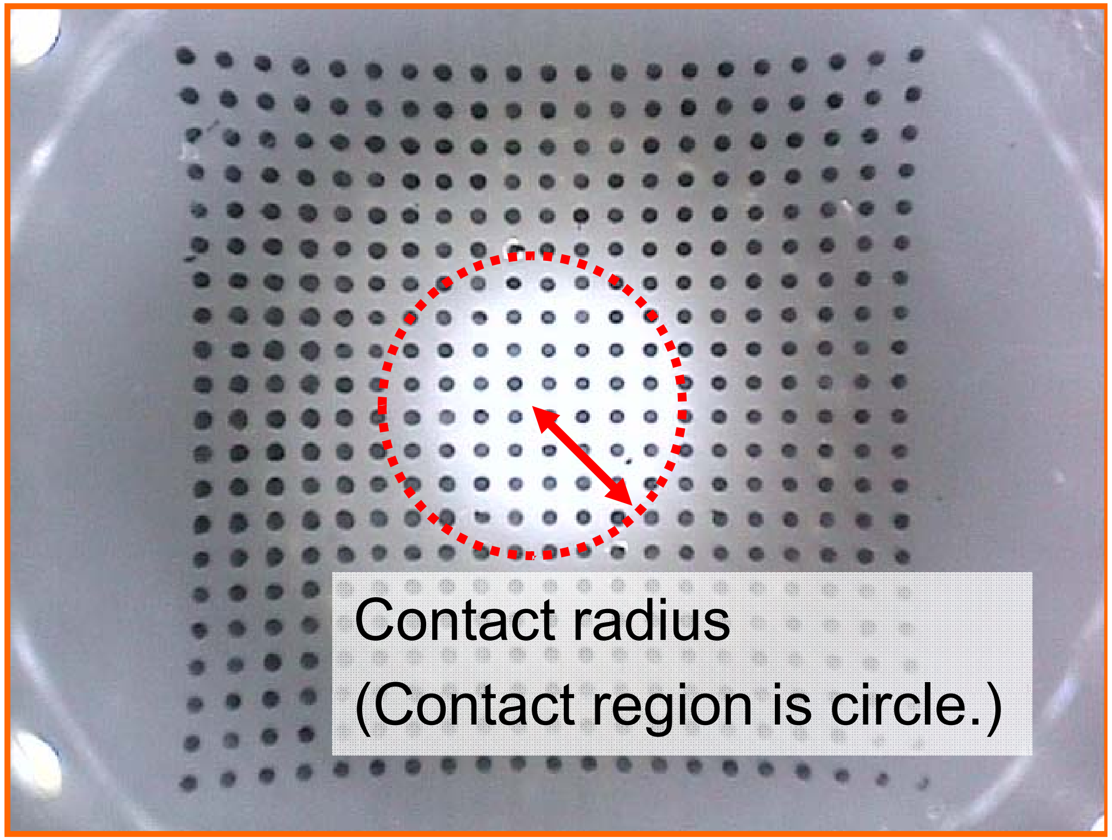


Measurement of Contact Force

- Normal force
- Tangential force
- Moment



Relation between normal force and contact radius

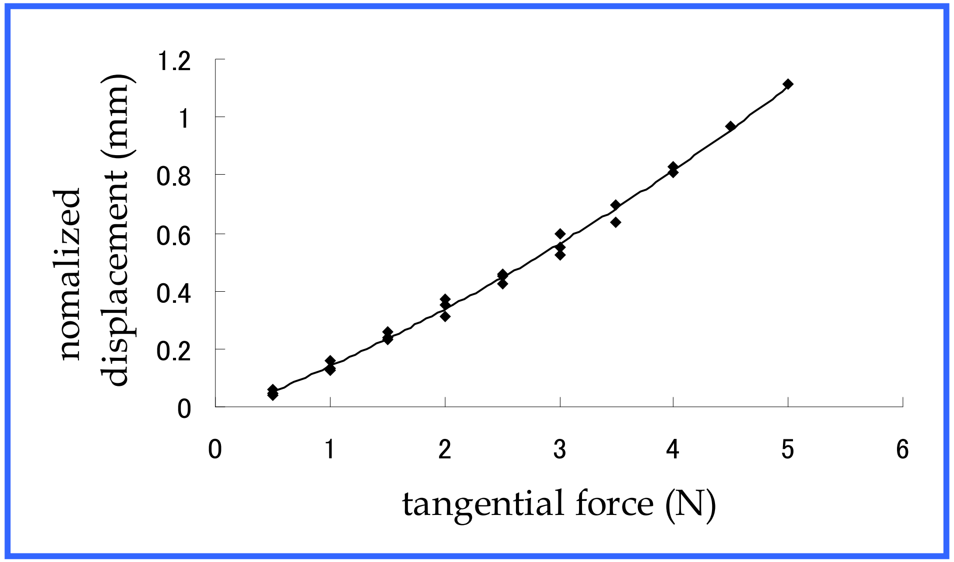


Refrence

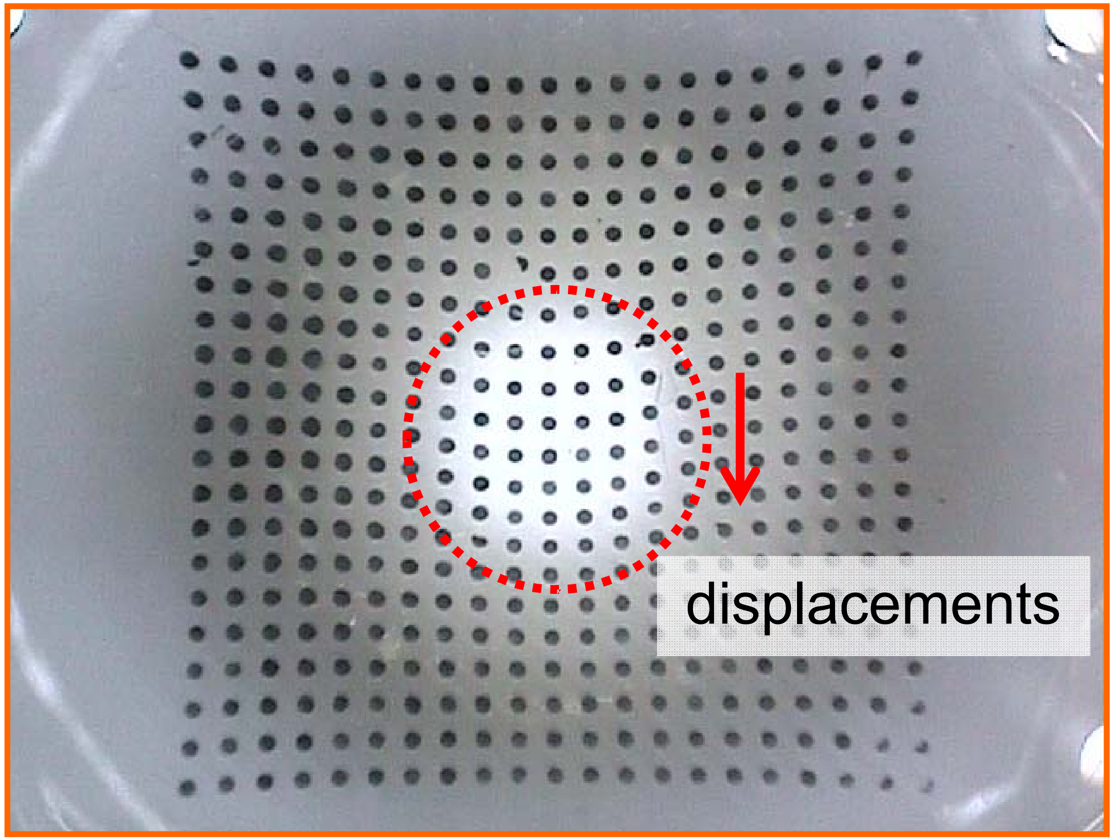
Xydas, Kao：Modeling of contact mechanics and friction limit surface for soft fingers in robotics with experimental results，International Journal of Robotics Research，Vol.18，No. 8，pp.941-950 (1999).

Measurement of Contact Force

- Normal force
- Tangential force
- Moment

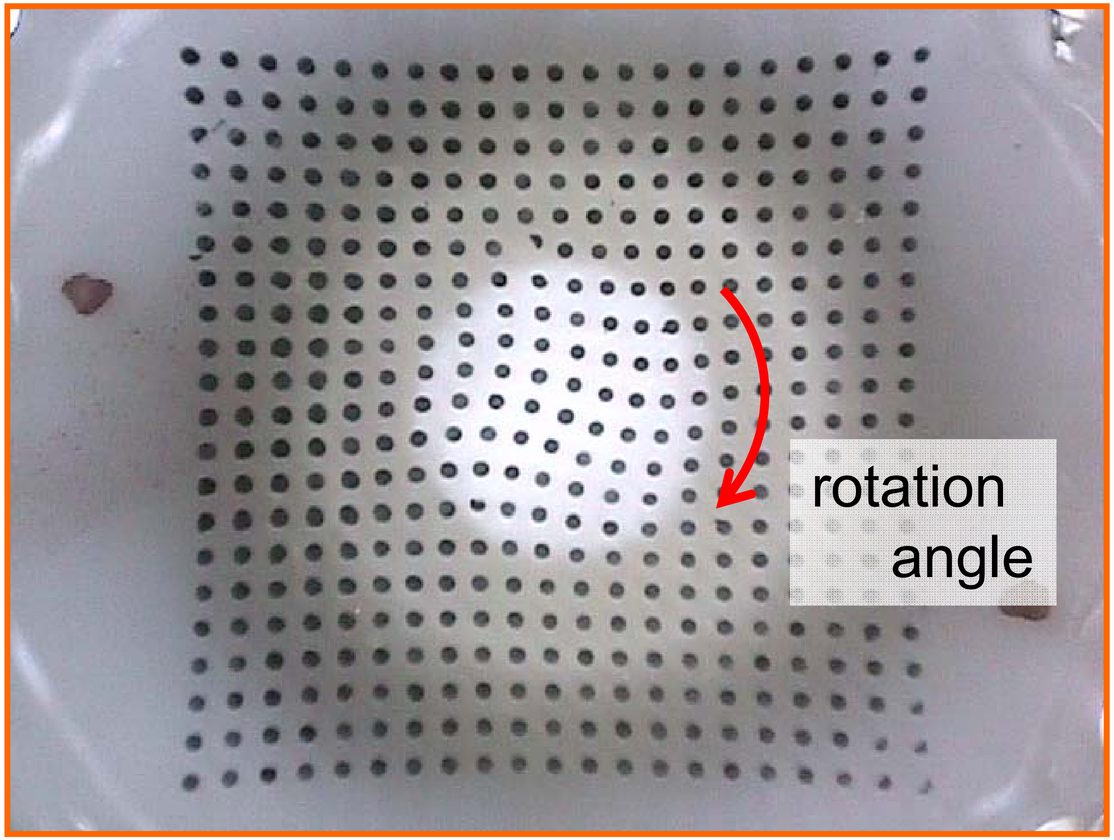


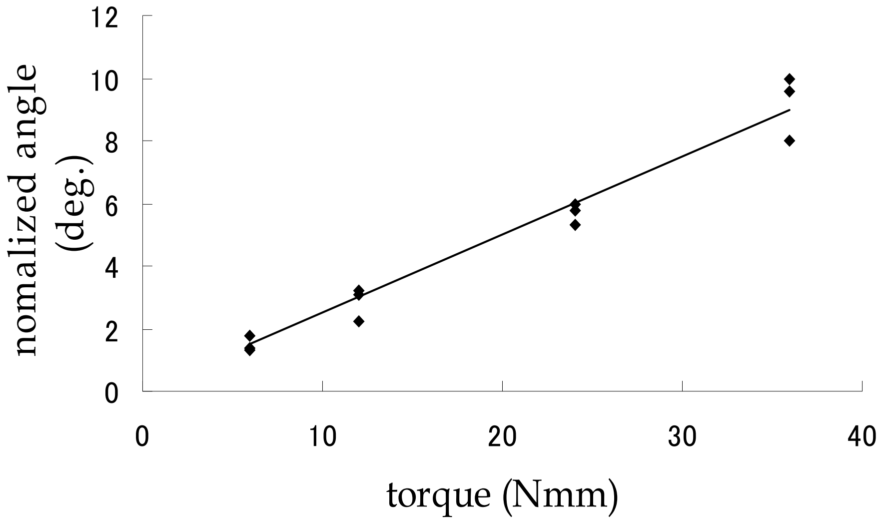
Relation between tangential force and displacements of dots



Measurement of Contact Force

- Normal force
- Tangential force
- Moment





Relation between moment
and rotation angle of contact surface

Forecasted Question

- 省略した内容も説明して
- 連続した同じ方向の巨視滑りに対する解決策は？
- 閾値はどうやって決めたの？
- 閾値は可変にしなくていいの？物性に依存しないの？
- 対象物との摩擦係数でφの検出可能範囲が変わるよね？
- 力と変位の関係は弾性体の物性に依存するよね？
- 固着率の真値は？
- 摩擦係数は取得できるの？
- 摩擦係数じゃ器用な把持は出来ないの？
- 接触方向は垂直のみに限られるの？転がり動作は無理？
- 他研究のセンサの滑り検出も、限られた場合しか出来ないの？
- 並進と回転が同時に起こっても測定できるの？
- なぜ滑り予知の推定が必要なの？
- 回転の中心はどうやって求めるの？
- 何故中心ドットとの相対変位なの？
- 物体の表面は平面じゃないと駄目なの？
- 動画にmacroscopic slippage が起こらないのでは？

Forecasted Question

力と変位の関係は弾性体の物性に依存するよね？

The relation between tangential force/moment and the displacement of dot depends on the elastic coefficient of the elastic body.

対象物との摩擦係数でφの検出可能範囲が変わるよね？

The smaller the friction coefficient is, the bigger the minimum value of the estimated stick ratio is. It is one of the future works.
However, the previous research shows that the range of the stick ratio is not so decreased if the friction coefficient is large in some measure (more than 1).

摩擦係数じゃ器用な把持は出来ないの？

I think that robot can grasp the unknown object by using the friction coefficient in some measure. However, we cannot use the coulomb friction law for the elastic body. And it is difficult to use the law when a moment is applied.
Moreover, it is well known that the friction coefficient is sensitive to several factors such as conditions of contact surface.

Forecasted Question

閾値は可変にしなくていいの？物性に依存しないの？

(It is desirable that δ_0 is small because the sensitivity of the slippage becomes higher.) It is enough if δ_0 is a size that the effect of the dot variations is hardly occurred. Therefore, δ_0 depends on the image resolution and number of pixels of the image, but doesn’t depend on the property of the object.

The results of two measures for selection of U depend on the grasped object, but we obtain similar results from other objects. The estimated stick ratio is not so different even though U is changed.

Therefore, these thresholds are not variable. However, It is considered that the thresholds become variable to change of the sensitivity for any purpose.

固着率の真値は？

For example, in nanometer scale, all region of the contact surface should slip even if macroscopic slippage doesn’t occur. So as to use the slippage degree effectively for the grip force control of hands, we have to define the border between sticking and slipping. Therefore, the true value is not exist and we should consider the optimal definition of the slippage degree for dexterous handling.

Forecasted Question

他研究のセンサの滑り検出も、限られた場合しか出来ないの？

There are not many researches which consider the slippage degree.
And as far as I can see, only our sensor can estimate the slippage degree in many cases introduced in this presentation.
In addition, only our sensor can estimate the contact force and slippage degree simultaneously.

なぜ滑り予知の推定が必要なの？

When the sensor cannot estimate the slippage degree, the robots may drop the grasped object due to delay of the control because the sensor cannot respond until macroscopic slippage occurs.
In addition, after the macroscopic slippage, the bigger grip force is required to stop the slippage since the friction coefficient decreases in the dynamic situation. It is desirable to respond before the macroscopic slippage occurs.

Forecasted Question

回転の中心はどうやって求めるの？

In the stick region, we obtain the same rotation angle regardless of used dots because dots in the stick region move and rotate uniformly.
And it is considered that the central dot remains in the stick region to the last moment until the stick ratio becomes to 0.

Therefore, we obtain the rotation angle in reference to central dot

何故中心ドットとの相対変位なの？

It is considered that the central dot remains in the stick region to the last moment until the stick ratio becomes to 0. Therefore, we estimate the slippage degree from the displacements of dots to the central dot.
(However, This is conventional concept. In this paper, we propose the reference dot instead of the central dot.)

物体の表面は平面じゃないと駄目なの？

For the curved surface whose curvature factor is small, we can estimate.
For the surface whose curvature factor is large, we will try as the future work.

Forecasted Question

動画にmacroscopic slippageが起こらないのでは？

Yes. There are two reasons why the stick ratio doesn't become 0.

First reason is that N_s doesn't become 0 because N_s includes the central dot.

Second reason is the accuracy of the estimation.

The dots close to central dot hardly move in reference to central dot.

However, the important thing is that we should control the grip force before the stick ratio becomes too small.

$$\phi = \frac{S_s}{S_c} = \frac{N_s}{N_c}$$

Estimation of ϕ with Distorted Stick Region (Case1)

Second point : ϕ Estimation timing

Estimate ϕ only when $d_{max} > U$

d_{max} : Maximum displacement of dot in stick region

U : threshold value

d_{max} : grows bigger when contact surface moves faster tangentially

$|d_0 - d_k| > \delta$ → Hardly satisfied, when d_{max} is small

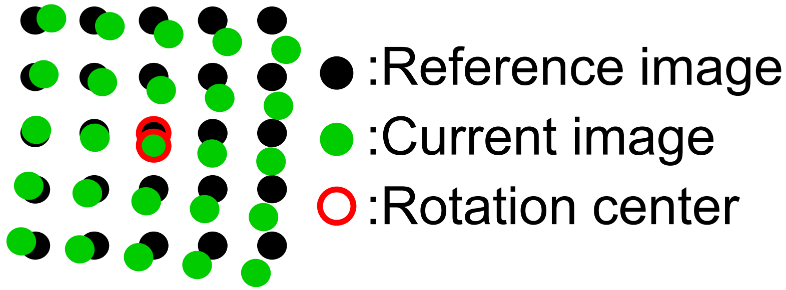
Estimation of ϕ with Applied Moment (Case2)

A long stick picking task

Sensor body and the stick rotate together

Most dots are regarded in slippage region

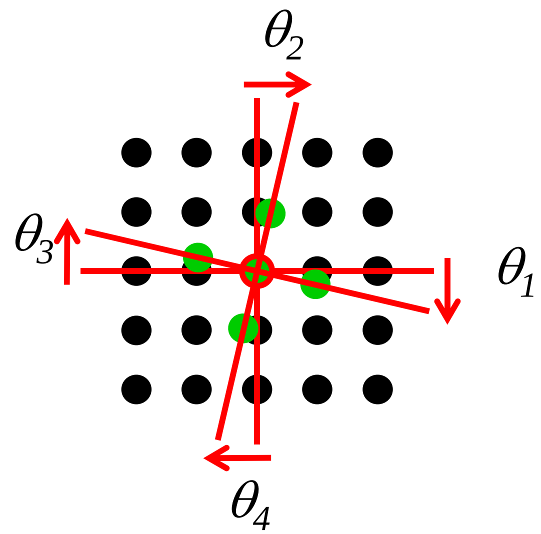
$$(\,|d_0 - d_k| > \delta\,)$$



After canceling the rotation component

obtain SD in the same way

Rotation angle $\theta_0 = \dfrac{\theta_1 + \theta_2 + \theta_3 + \theta_4}{4}$

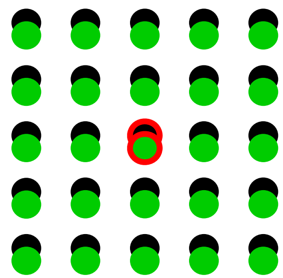


Rotation equation

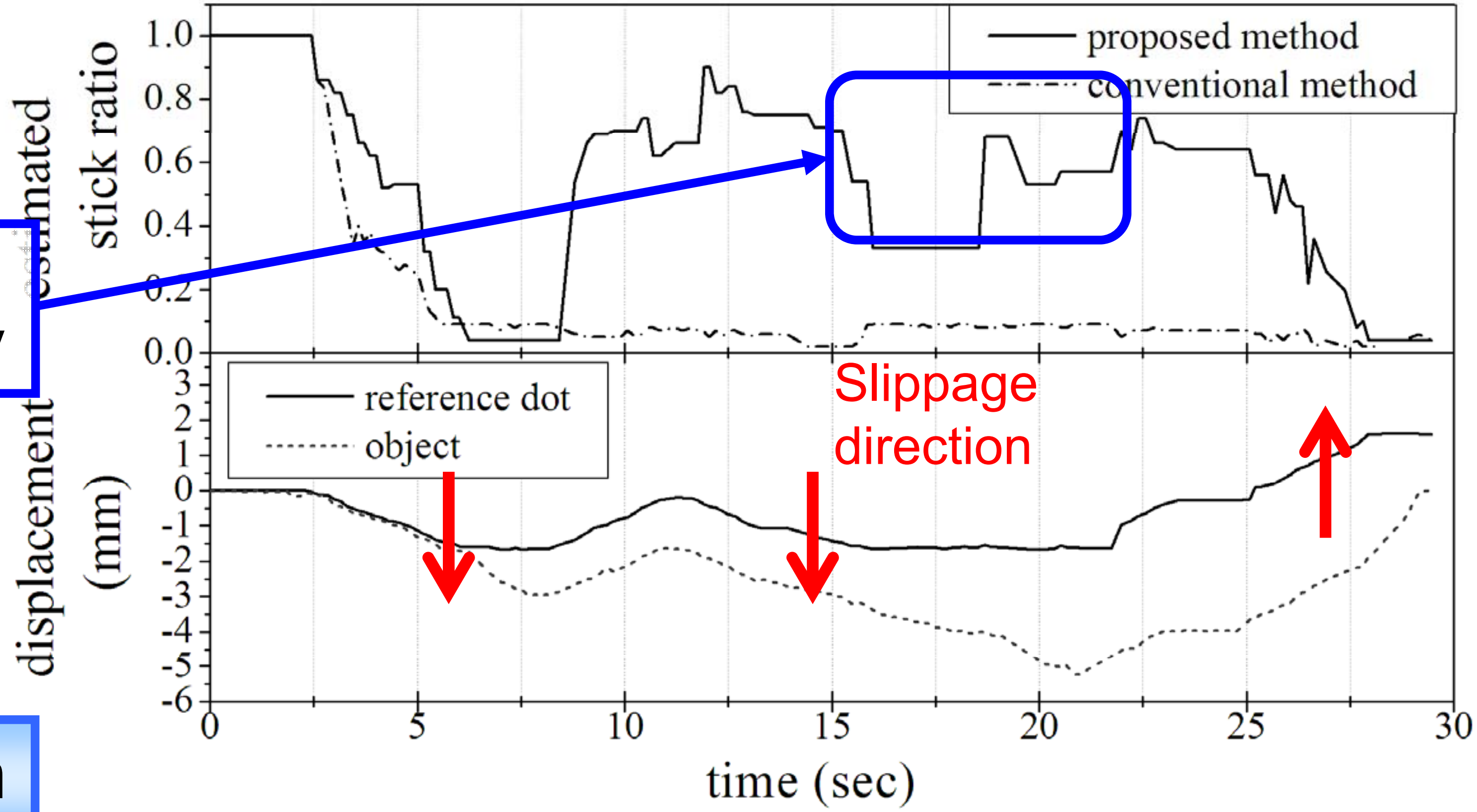
$$p_{post_k} = \begin{bmatrix} \cos\theta_0 & \sin\theta_0 \\ -\sin\theta_0 & \cos\theta_0 \end{bmatrix} \left(p_{pre_k} - p_{pre_0}\right) + p_{post_0}$$

p_k: Each dot position *pre*: Before rotation

p_0: Central dot position *post*: After rotation



Another Approach for Estimation of Slippage Degree



Not good in the same direction continuously

Another approach

Measure when macroscopic slippage

- Normal force N_0
- Tangential force F_0

Comparing

$$\mu \cong \frac{F_0}{N_0} \Leftrightarrow \frac{F}{N}$$

F : Current tangential force

N : Current normal force

→ Prediction of macroscopic slippage

Shape Sensing by Vision-Based Tactile Sensor for Dexterous Handling of Robot Hands

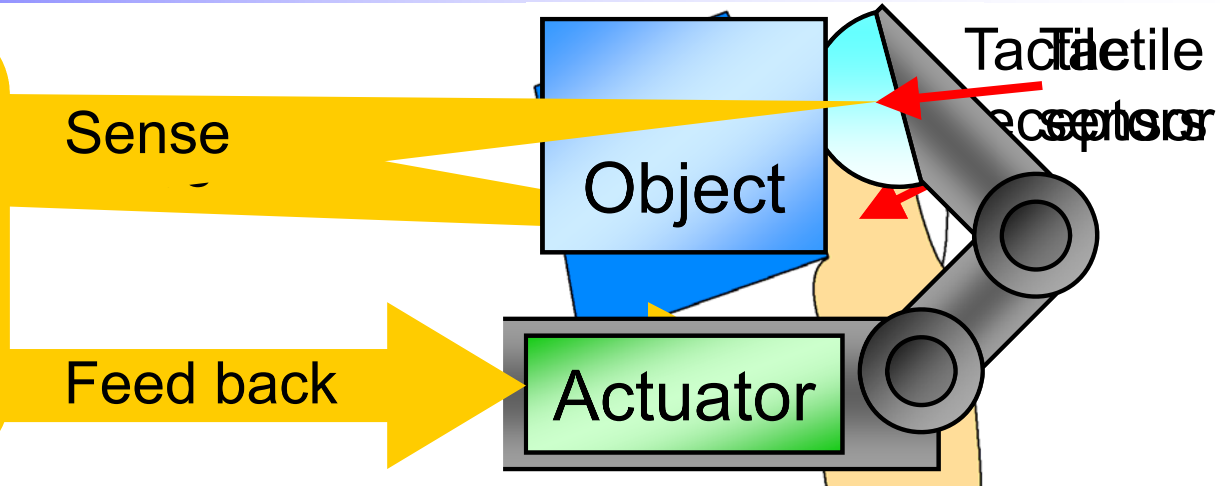
Table of Contents

1. Introduction
2. Vision-Based Tactile Sensor
3. Shape Sensing Method
4. Experimental Results
5. Conclusion

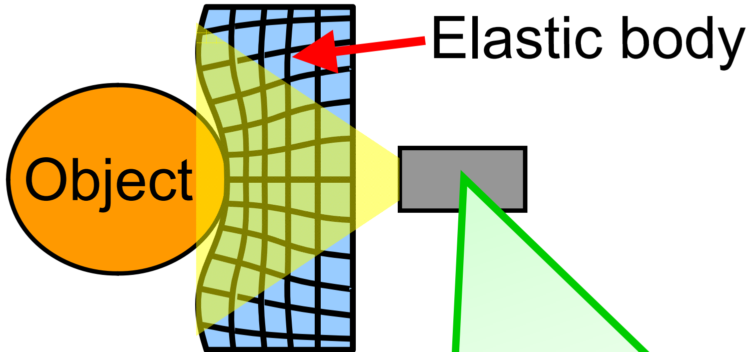
Background

Dexterous handling of object by robot hand

Tactile information
- Contact force
- Slippage
- Shape/irregularity
- Temperature etc…



Vision-based tactile sensor has desirable structure.*



Camera capturing deformation

Analyzing

Tactile information

Problems of other sensors
(resistive, capacitive, piezoelectric, etc)
- Many devices and wiring are needed.
- Elastic body decreases sensitivity.

Vision-based sensors doesn't have such problems.

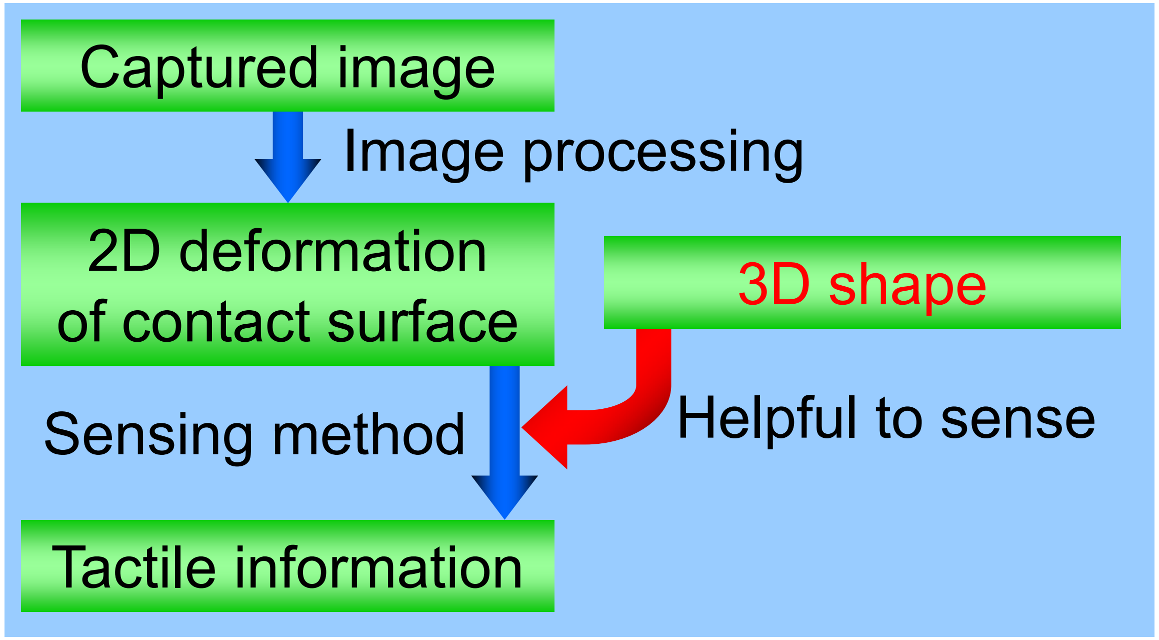
*:K. Kamiyama (*IEEE Computer Graphics and Applications*, 2005), S. Saga (*Sensor Review, 2007*)

Purpose

Sense of object shape/irregularity allows to...

- Archive tasks requiring shape recognition
- Choose grasping strategy
- Provide detailed information to methods sensing other tactile information

etc…



Problem of shape sensing by vision-based sensor

- Using only single camera for compactness

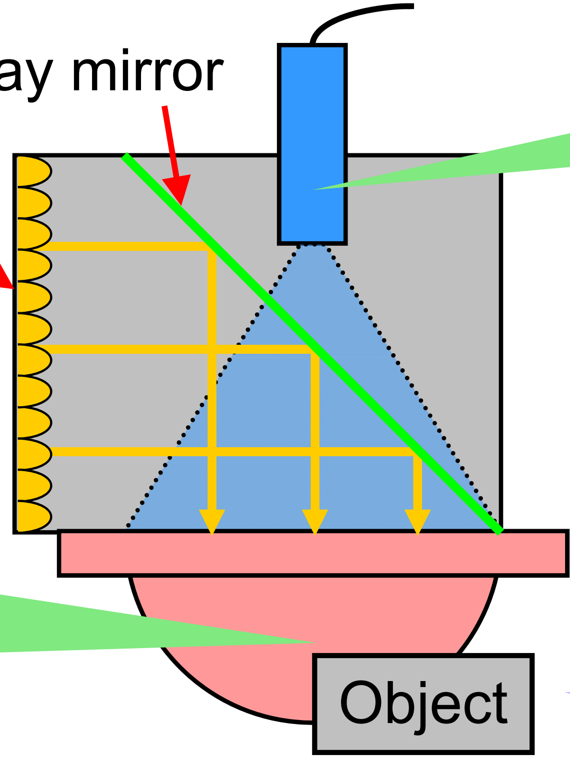
Obtain 3D information of contact surface from 2D single image

Purpose

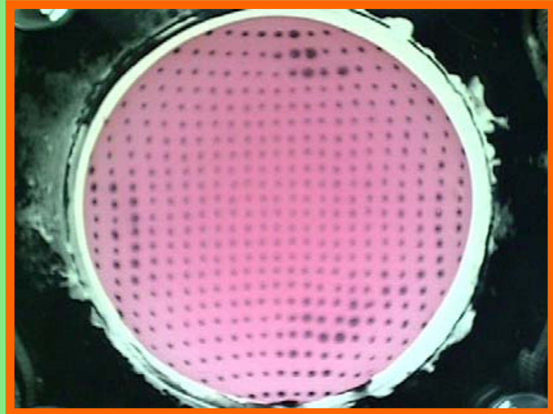
Estimating 3D shape/irregularity of objects by single camera

Table of Contents

Structure of Vision-Based Tactile Sensor



CCD camera

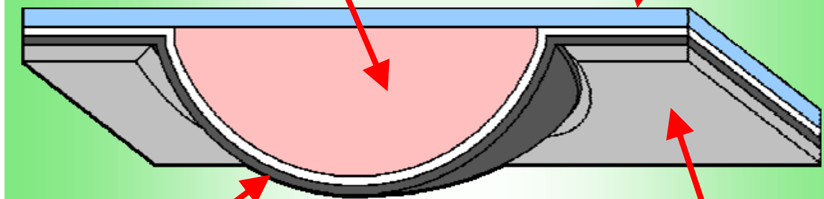


Analysis of
{ dot positions
contact region

Touch pad

Transparent acrylic plate

Translucent red water



Metal plate

Two-layered elastic membranes
- Outer : Black color
- Inner : White color,
  Printed dotted pattern

Acquisition of tactile information

- Contact force*
  (normal, tangential, moment)
- Slippage degree**
- Object shape/irregularity

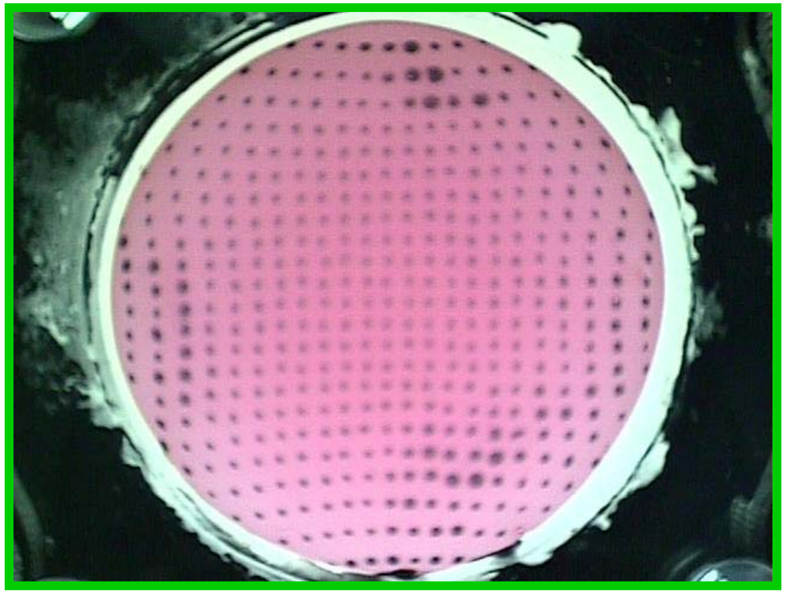
*:G. Obinata (*Mobile Robots: Perception & Navigation*, 2007), **:Y. Ito (*IEEE SENSORS*, 2009)

Table of Contents

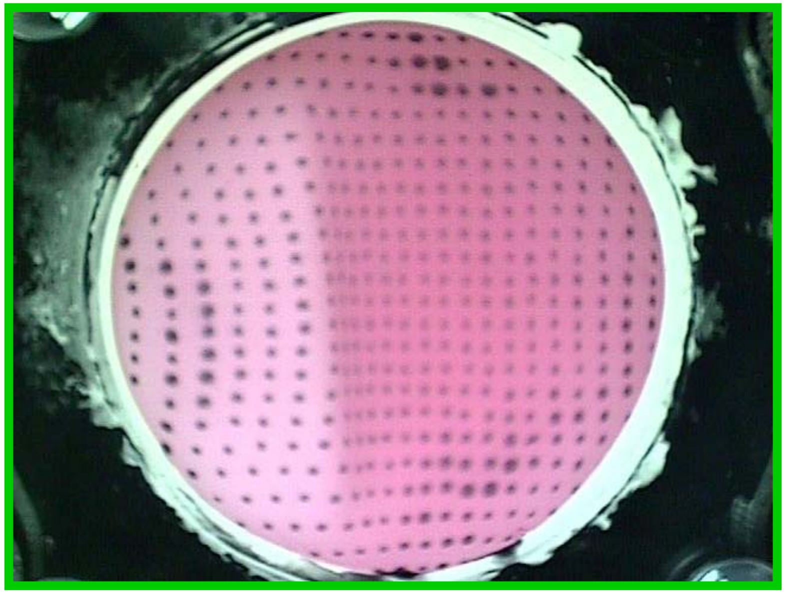
Fundamental Principle of Shape Sensing

Color in image changes depending on shape of touch pad.

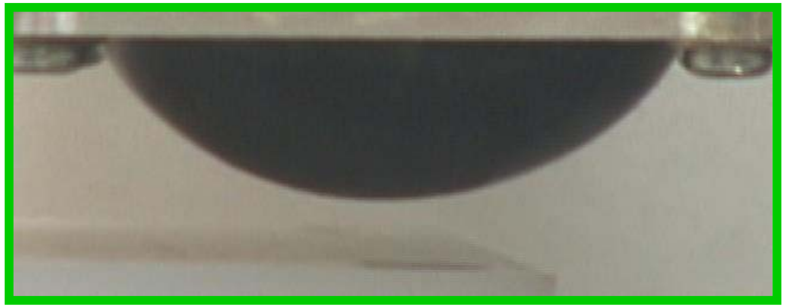
Captured image



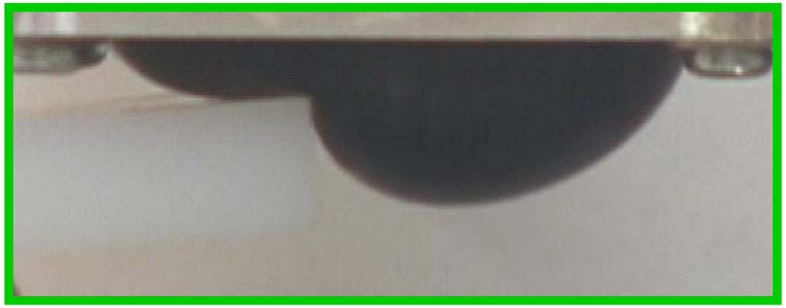
Change of color



Side view of touch pad



Change of shape



Fundamental Principle of Shape Sensing

Main content of shape sensing

Definition : Region V_i is projected on Pixel P_i in image.

Significant relationship

Depth of touch pad

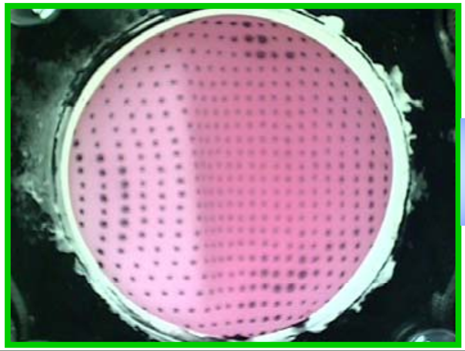
↕ Dependency

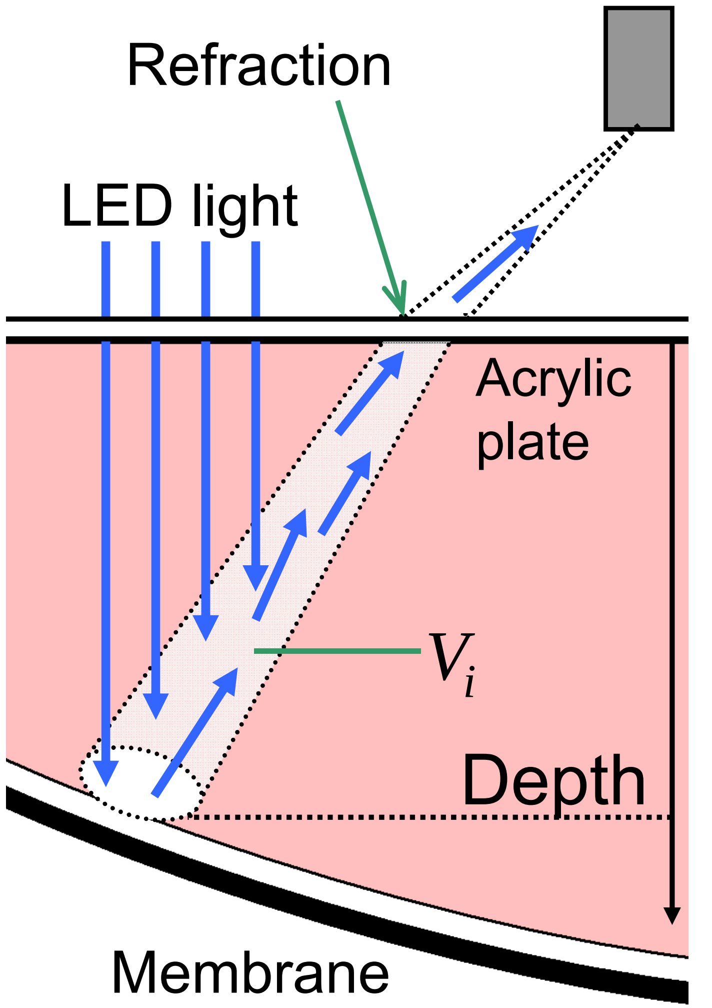
Light intensity in V_i (Input signal of CCD)

↕ Proportionality

Color intensities (RGB values) of P_i

We can calculate shape of pad from RGB values.





Formulation of Shape Sensing Method

1. Finding relationship among color, light intensity and depth

2. Eliminating parameters

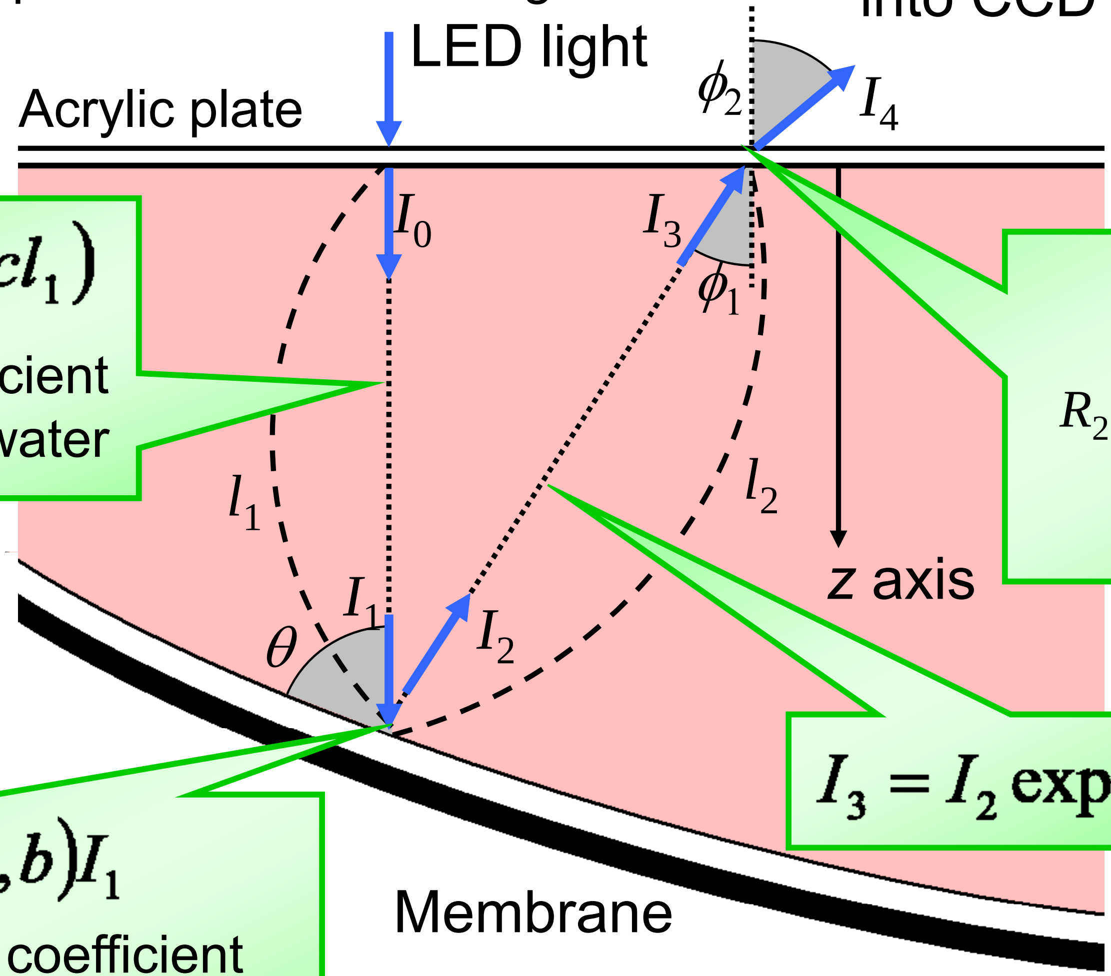
3. Determining unknown parameters

4. Compensating Approximation errors

Relationship among Color, Light Intensity and Depth

LED light reflects off membrane and travels into CCD

I_0, I_2, I_3, I_4 : Intensity per unit area of LED light



$$I_1 = I_0 \exp(-cl_1)$$

c : Extinction coefficient in colored water

$$I_4 = R_2 I_3$$

R_2 : Transmission coefficient to acrylic plate

$$I_3 = I_2 \exp(-cl_2)$$

$$I_2 = R_1(\theta, b) I_1$$

$R_1(\theta,b)$: Reflection coefficient to membrane

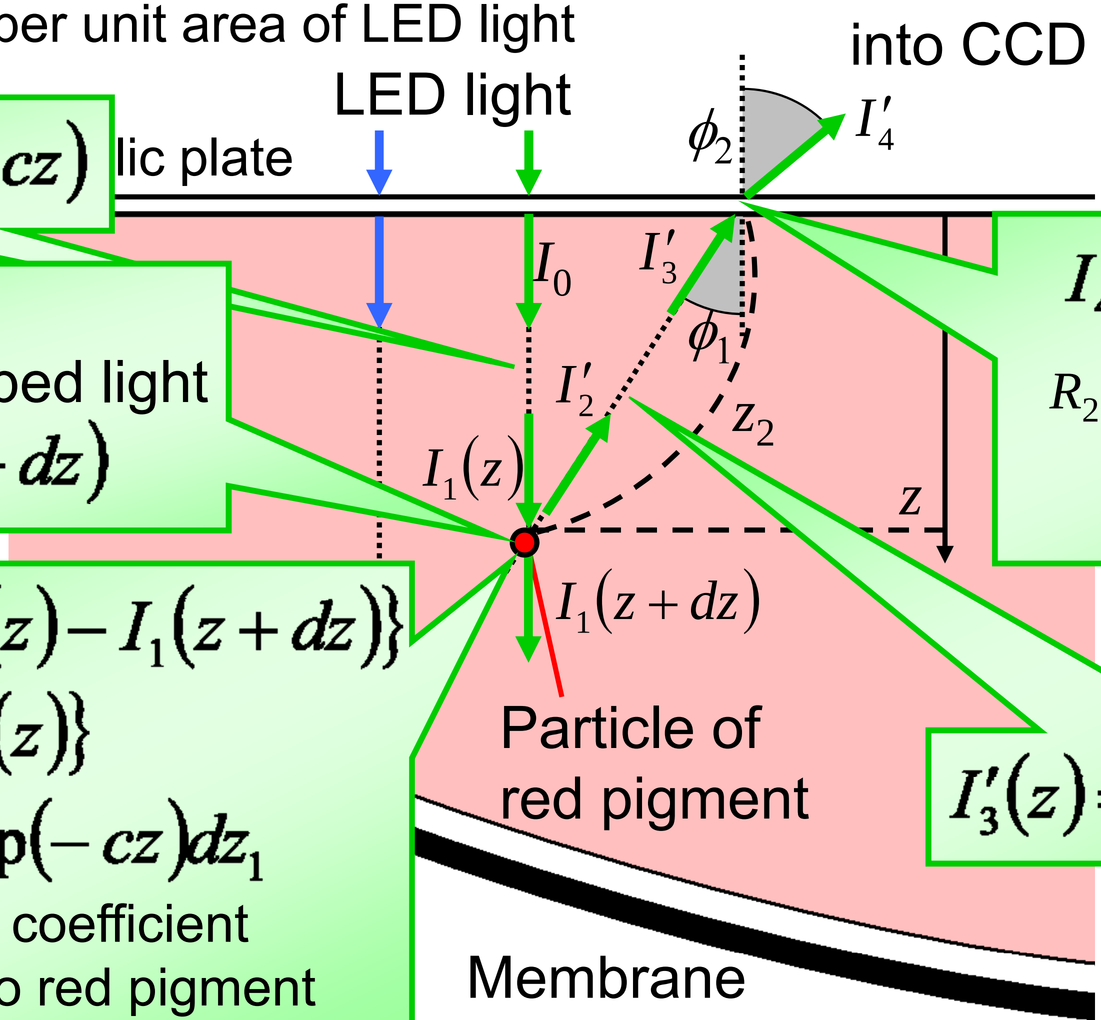
b : Color of inner membrane

$$I_4 = R_1(\theta, b) R_2 I_0 \exp\{-c(l_1 + l_2)\}$$

Relationship among Color, Light Intensity and Depth

LED light reflects off red pigment and travels into CCD

I'_2, I'_3, I'_4 : Intensity per unit area of LED light



$$I_1(z) = I_0 \exp(-cz)$$

Intensity of scattered/absorbed light

$$I_1(z) - I_1(z+dz)$$

$$I'_2(z) = R'_1(\phi_1)\{I_1(z) - I_1(z+dz)\}$$
$$= R'_1(\phi_1)\{-dI_1(z)\}$$
$$= cR'_1(\phi_1) I_0 \exp(-cz) dz_1$$

$R'_1(\phi_1)$: Scattering coefficient to red pigment

$$I'_4(z_2) = R_2 I'_3(z_2)$$

R_2 : Transmission coefficient to acrylic plate

$$I'_3(z) = I'_2(z)\exp(-cz_2)$$

$$I'_4(z_2) = cR'_1(\phi_1) R_2 I_0 \exp\{-c(z+z_2)\} dz \equiv I'_5(z_2) dz$$

Relationship among Color, Light Intensity and Depth

Sum of light intensity I_{sum} in region V_i

$$I_{sum} = SI_4 + \int_0^{l_1} S'(z) I_5'(z) dz \equiv f_1(I_0, l_1, c, R_1, R_1')$$

S : Area on membrane in V_i

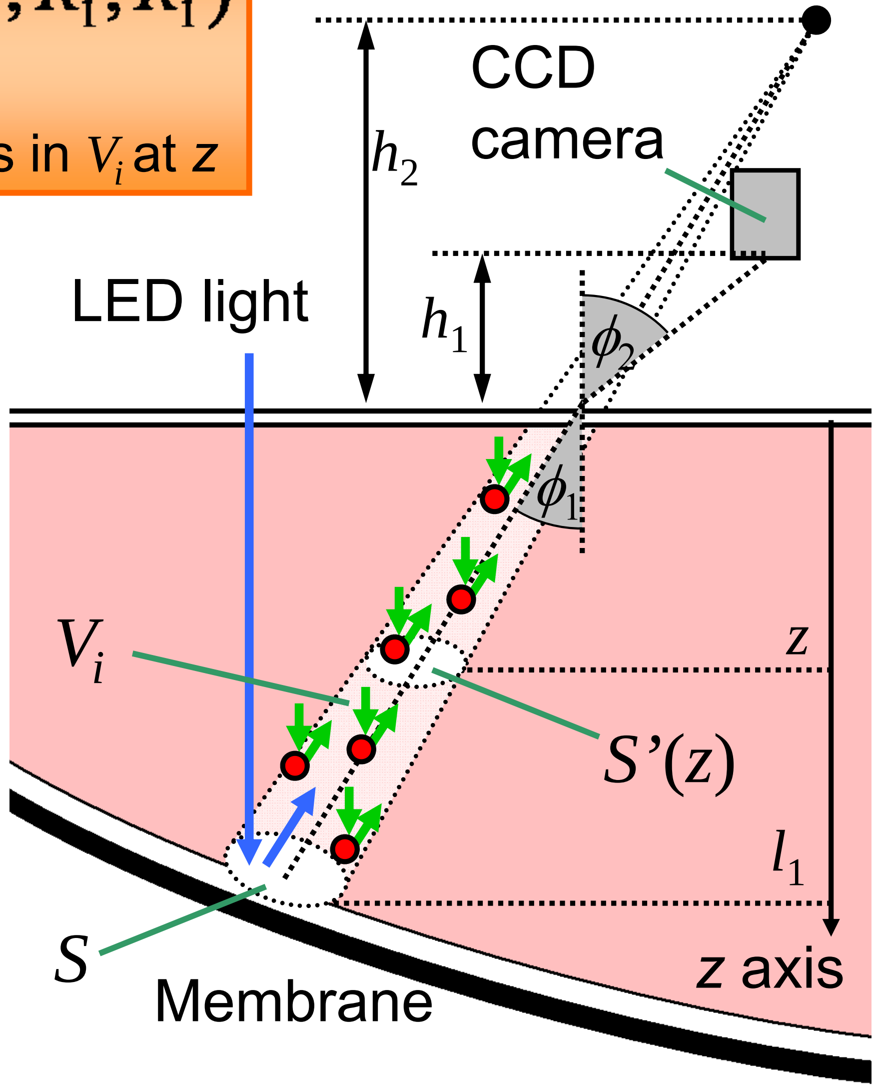
$S'(z)$: Area on plane vertical to z axis in V_i at z

Geometrical relationship

$$S'(z) = s(z + h_2)^2$$

(Detail is abbreviated.)

s : Proportional constant h_2 : Obtained from h_1



Applying to RGB components

$$b_R / \beta_R = f_1(\alpha_R I_0, l_1, c_R, R_1, R_{R1}')$$

$$b_G / \beta_G = f_1(\alpha_G I_0, l_1, c_G, R_1, R_{G1}')$$

$$b_B / \beta_B = f_1(\alpha_B I_0, l_1, c_B, R_1, R_{B1}')$$

b_R, b_G, b_B:RGB values in image

α_R, α_G, α_B, β_R, β_G, β_B : Propotional constants

Formulation of Shape Sensing Method

1. Finding relationship among color, light intensity and depth

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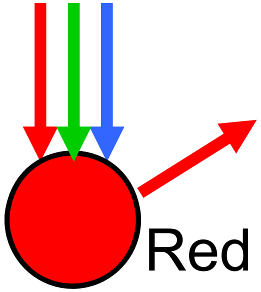
Eliminating Parameters

Approximation of scattering coefficients $R'_1(\phi_1)$

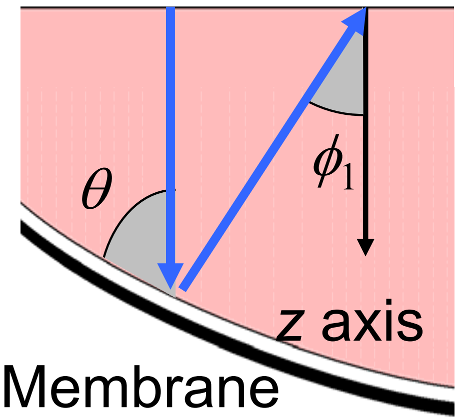


- R component of light is scattered. $R'_{R1}(\phi_1) > 0$
- G/B component of light is absorbed. $R'_{G1}(\phi_1) \cong 0$ $R'_{B1}(\phi_1) \cong 0$

Elimination of R_1 depending angle θ and color b of membrane

$$\begin{cases} b_R/\beta_R = f_1(\alpha_R I_0, l_1, c_R, R_1, R'_{R1}) \\ b_G/\beta_G = f_1(\alpha_G I_0, l_1, c_G, R_1, R'_{G1}) \\ b_B/\beta_B = f_1(\alpha_B I_0, l_1, c_B, R_1, R'_{B1}) \end{cases}$$

Solving simultaneous equations of R and G components (R and B)



$$g(\phi_1) = \frac{b_G \exp(c_G k l_1) - \kappa b_R \exp(c_R k l_1)}{Q_1(c_R)\{1-\exp(c_R k l_1)\} + Q_2(l_1, c_R)} \equiv f_2(l_1, b_R, b_G)$$

$$g(\phi_1) = \alpha_G \beta_G s R_2 R'_{R1}(\phi_1) I_0 = const$$

$\kappa = \beta_G \alpha_G / \alpha_R \beta_R$ $\quad k(\phi_1) = 1 + 1/\cos\phi_1$ $\quad Q_1, Q_2$: Polynomial function of l_1, c_R, h_2 and k

Formulation of Shape Sensing Method

1. Finding relationship among color, light intensity and depth

2. Eliminating parameters

3. Determining unknown parameters

4. Compensating Approximation errors

Determining Unknown Parameters

Determining $g(\phi_1)$ by using measured values

$$f_2(l_1, b_R, b_G) = g(\phi_1) = f_2(l_1(t_0), b_R(t_0), b_G(t_0))$$ ← Known

$l_1(t_0)$, $b_R(t_0)$, $b_G(t_0)$: Previously measured initial values

Parameter identification of c_R, c_G and κ

$$\frac{b_G \exp(c_G k l_1) - \kappa b_R \exp(c_R k l_1)}{Q_1(c_R)\{1 - \exp(c_R k l_1)\} + Q_2(l_1, c_R)} = f_2(l_1(t_0), b_R(t_0), b_G(t_0))$$

Previously measured

$$\begin{cases} l_1(t_1), b_R(t_1), b_G(t_1) \\ l_1(t_2), b_R(t_2), b_G(t_2) \\ l_1(t_3), b_R(t_3), b_G(t_3) \end{cases}$$

Solving simultaneous equations

c_R, c_G and κ are obtained.

Equation to calculate pad depth l_1 from color intensities b_R, b_G

$$f_2(l_1(t), b_R(t), b_G(t)) = f_2(l_1(t_0), b_R(t_0), b_G(t_0))$$

Formulation of Shape Sensing Method

1. Finding relationship among color, light intensity and depth

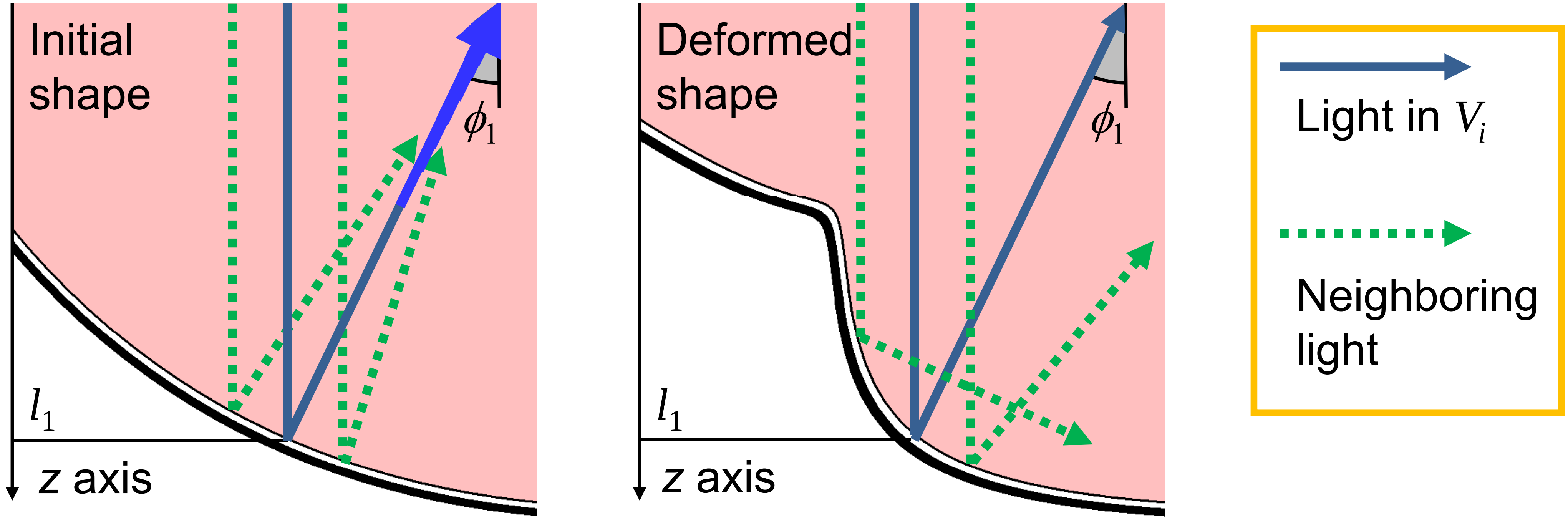
2. Eliminating parameters

3. Determining unknown parameters

4. Compensating Approximation errors

Compensation for Approximation Error

Effect of neighboring light



Neighboring light increases light intensity in V_i.

Neighboring light travels in different direction.

$$f_2(l_1(t), b_R(t), b_G(t)) = f_2(l_1(t_0), b_R(t_0), b_G(t_0))$$

Calculating in reference to initial shape

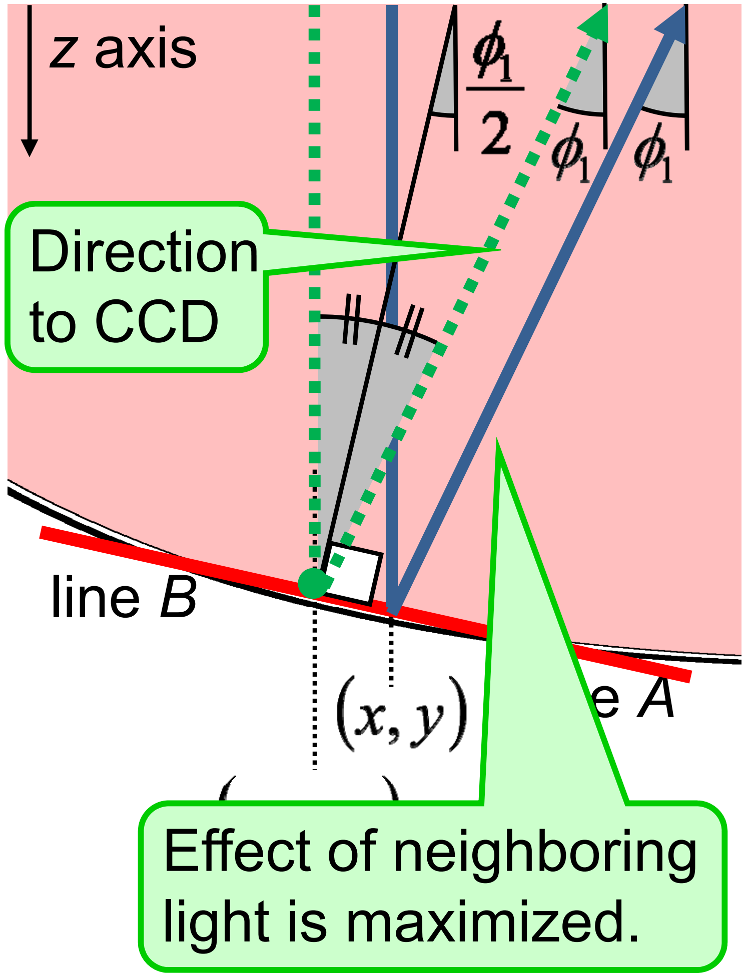
Assumption : Error of depth l_1 depends on…

- Deformation of membrane
- Pad depth

} in reference to initial shape

Compensation for Approximation Error

Parameters to represent degree of deformation/depth



ψ_{sum} : Deformation of membrane

Difference from initial shape

$$\psi_{sum}(x,y,t) = \sum_k \{\psi(x_k, y_k, t) - \psi(x_k, y_k, t_0)\}$$

Small area : $\left(\sqrt{(x_k - x)^2 + (y_k - y)^2} \leq r\right)$

r : Threshold value

m : Scale parameter depending on depth

Difference from initial shape

$$m = m_0 \exp[n\{l_1(x,y,t) - l_1(x,y,t_0)\}]$$

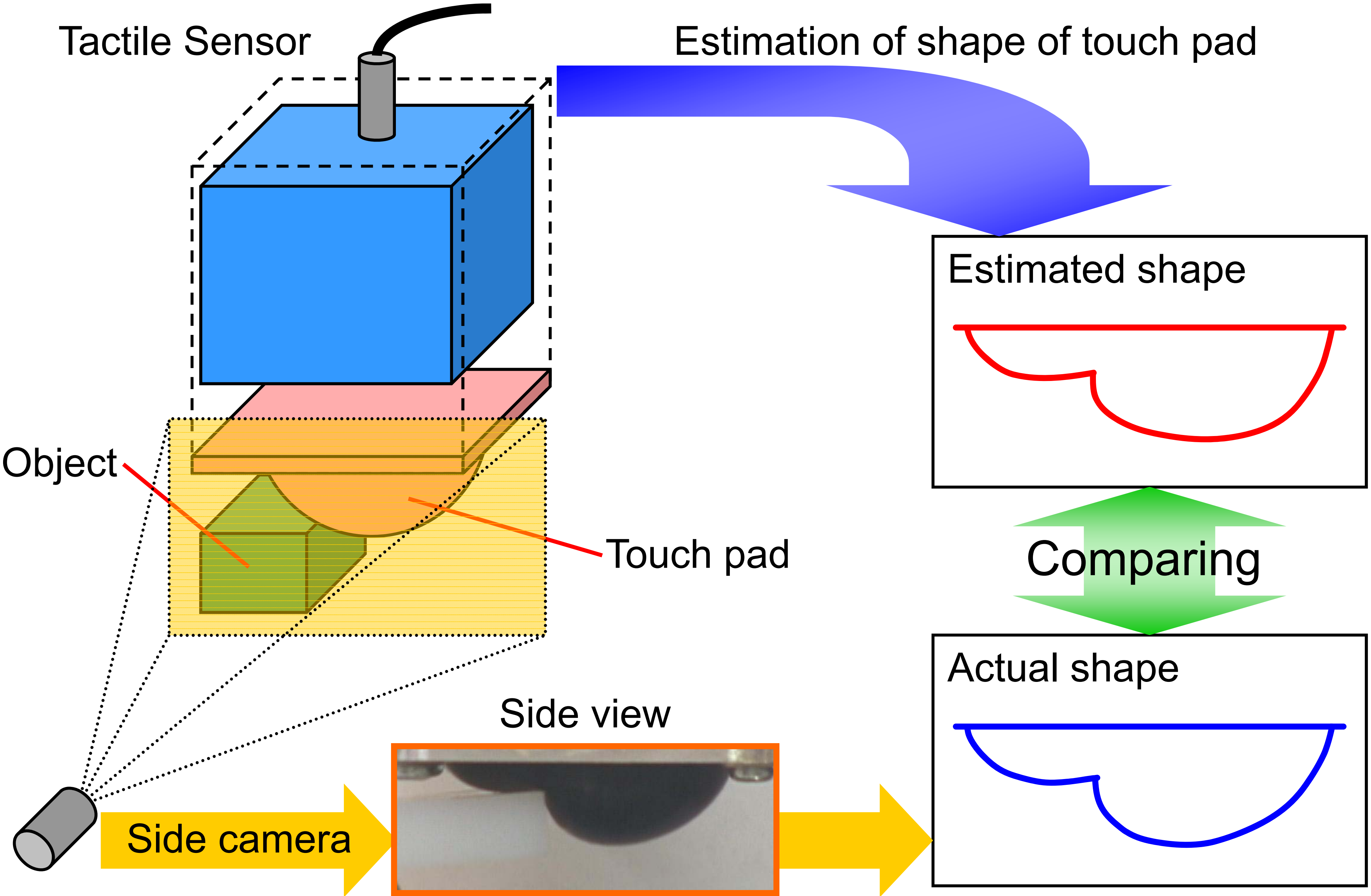
m_0, n : Threshold value

Equation to compensate depth l_1

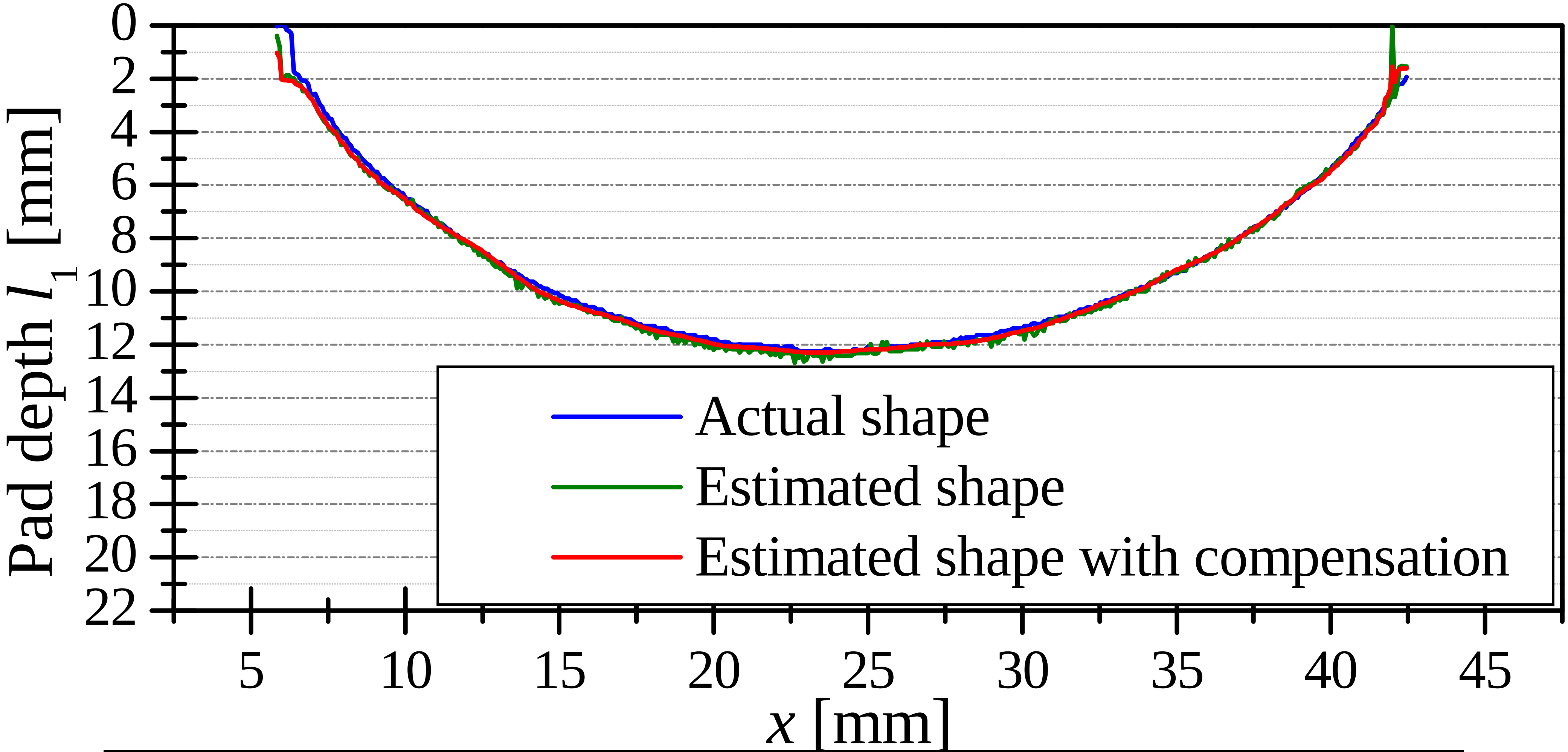
Compensated depth : $l_1'(x,y,t) = l_1(x,y,t) - m\psi_{sum}(x,y,t)$

Table of Contents

Experimental Description

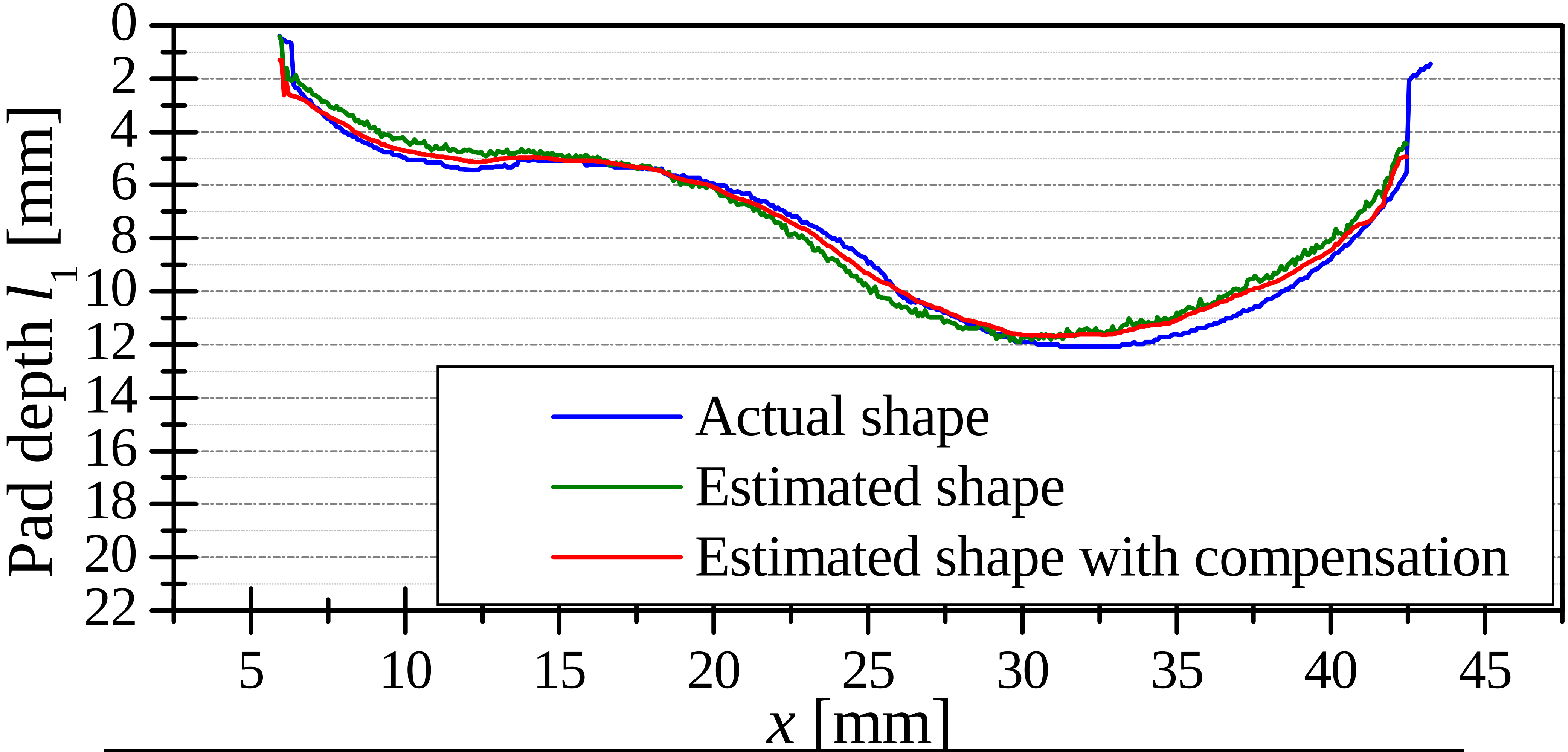


Result of Shape of Non-Contact Touch Pad



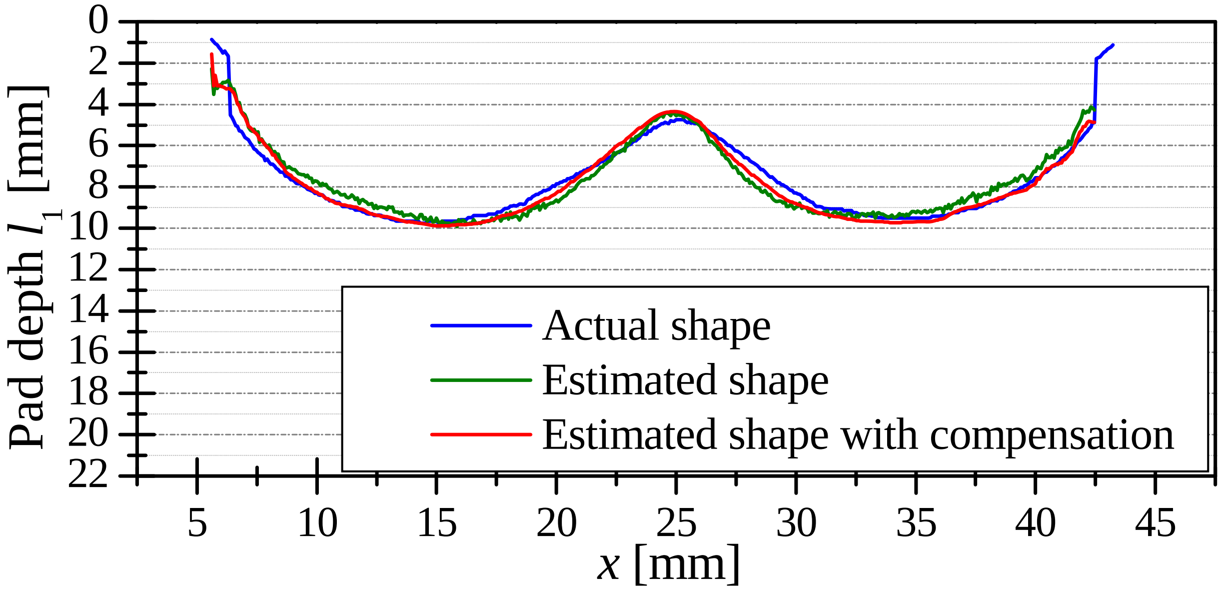
	Mean error [mm]	Standard deviation [mm]
Without compensation	0.16	0.10
With compensation	0.10	0.07

Result of Shape of Contacting Touch Pad (1)

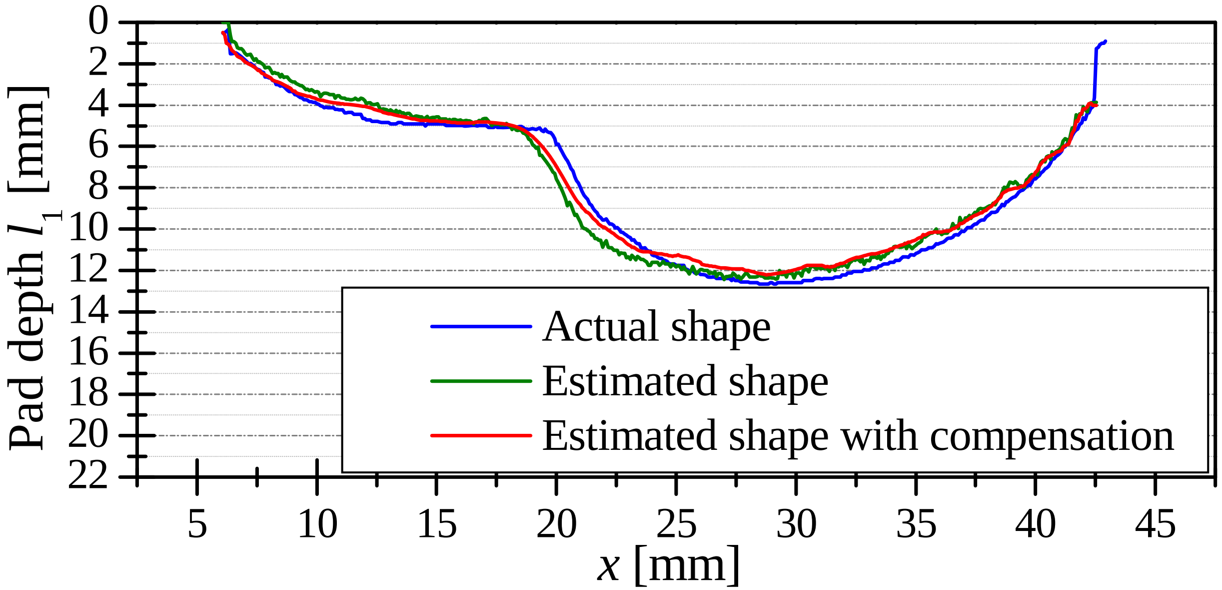


	Mean error [mm]	Standard deviation [mm]
Without compensation	0.53	0.29
With compensation	0.30	0.20

Result of Shape of Contacting Touch Pad (2)



	Mean error [mm]	Standard deviation [mm]
Without compensation	0.43	0.25
With compensation	0.25	0.18



	Mean error [mm]	Standard deviation [mm]
Without compensation	0.53	0.39
With compensation	0.43	0.24

Experimental Movie

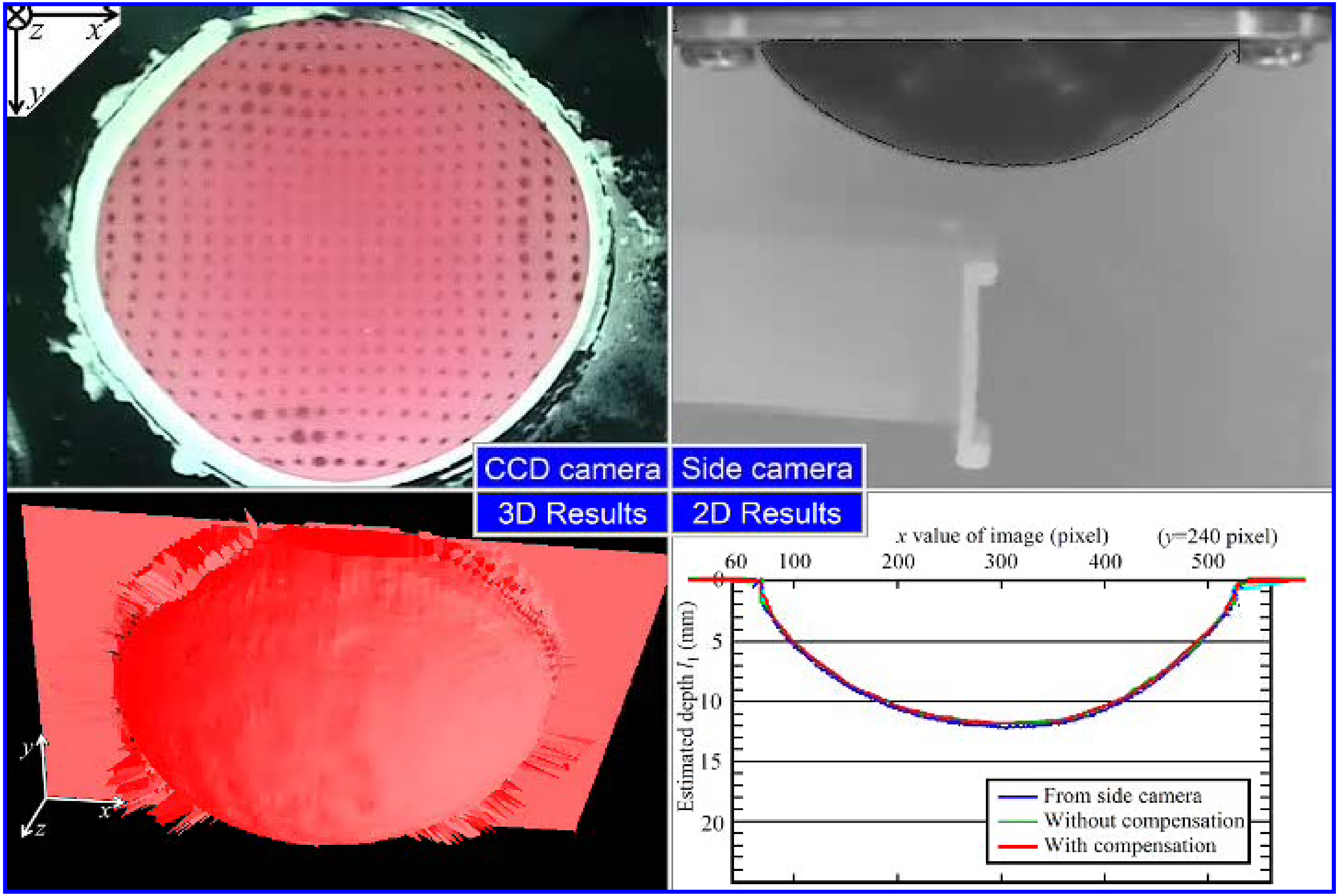


Table of Contents

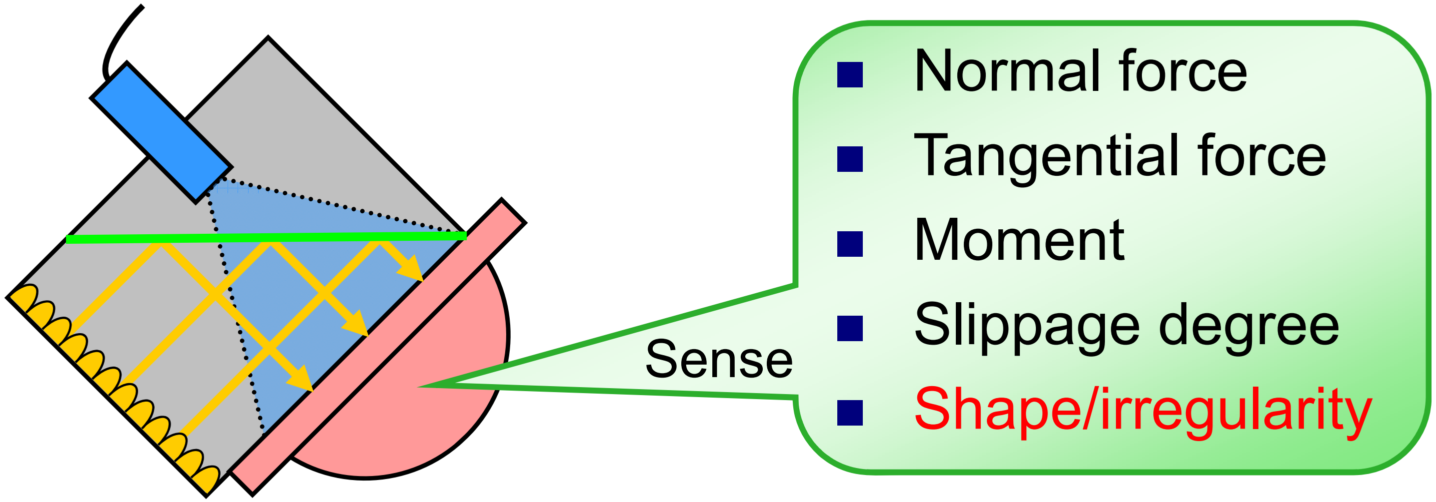
1. Introduction
2. Vision-Based Tactile Sensor
3. Shape Sensing Method
4. Experimental Results
5. Conclusion

Conclusion

This paper proposed …

- Method to obtain shape/irregularity of object by using only single camera

Our sensor was developed to practical level.

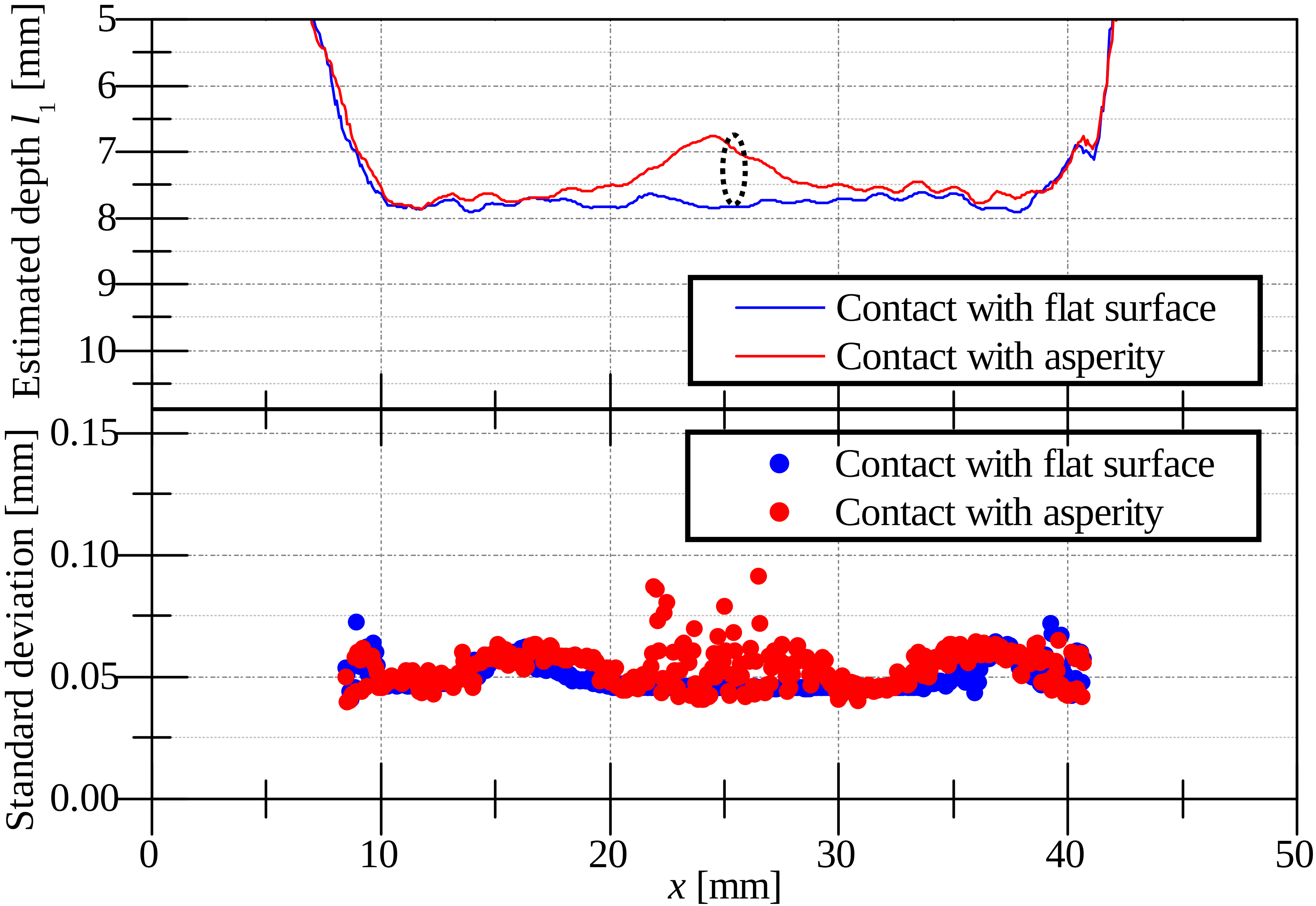


Future work

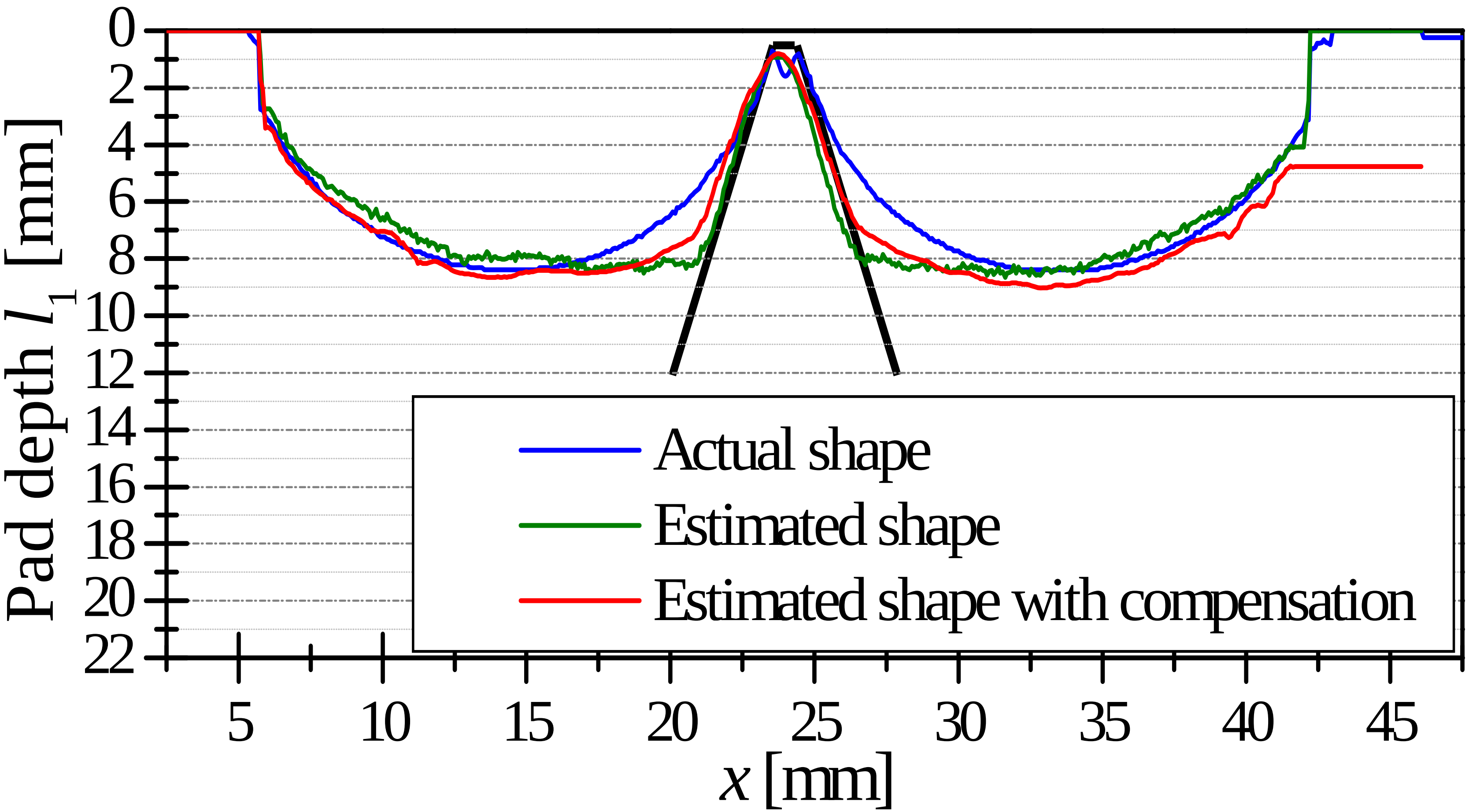
Implementation of developed sensor to robot hand to verify proposed method

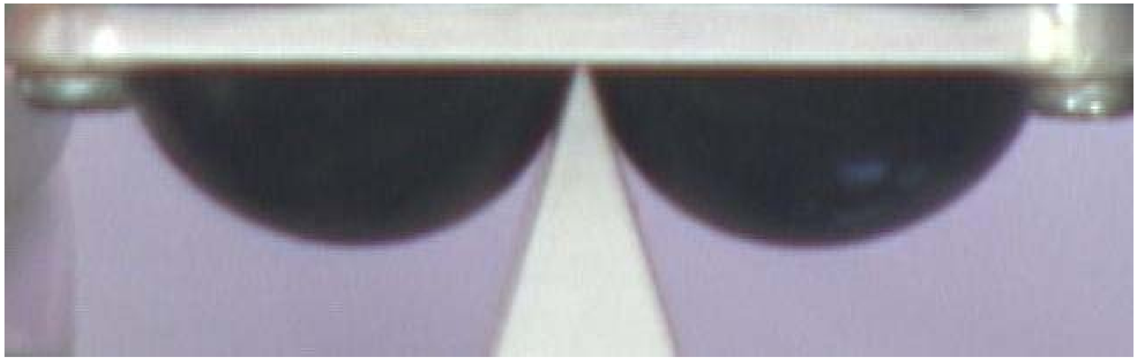
Thank you for your kind attention.

Estimation Result of Irregularity of Object



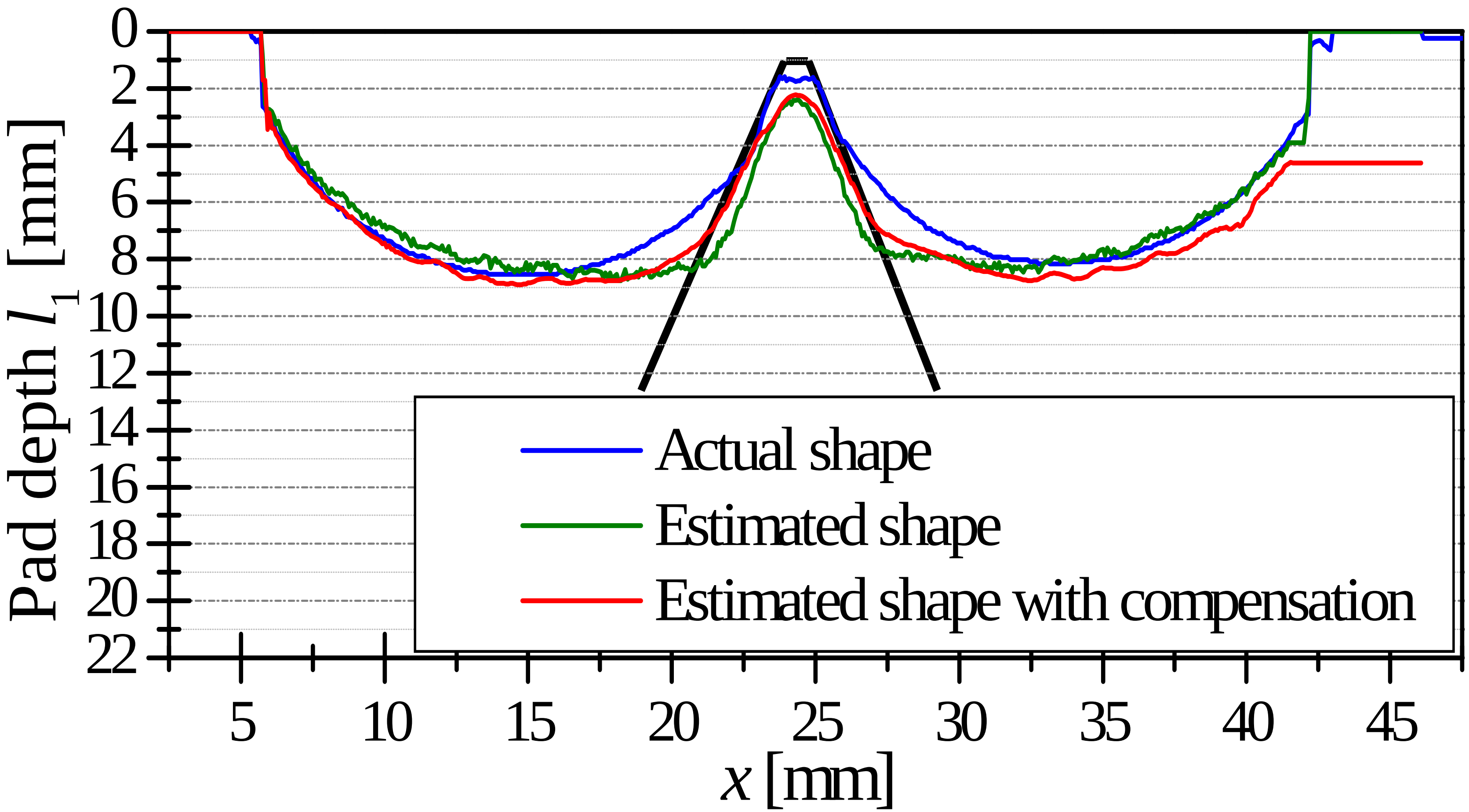
Limitation of Shape of Object

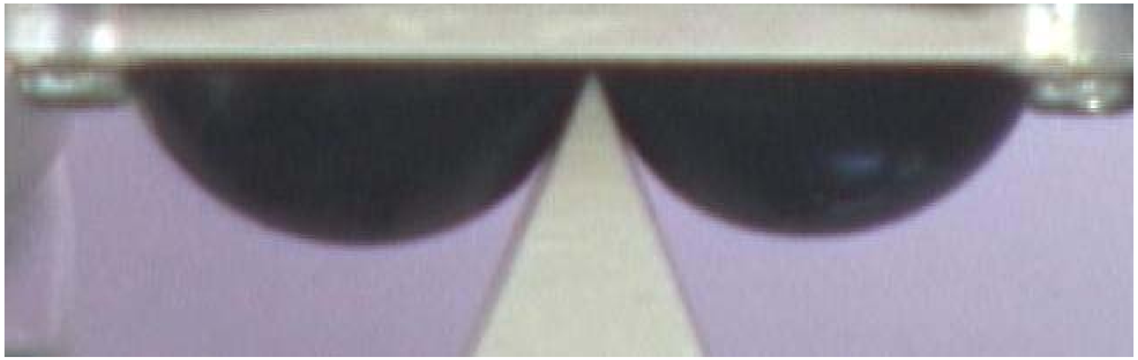




	Mean error [mm]	Standard deviation [mm]
Without compensation	0.72	0.70
With compensation	0.58	0.42

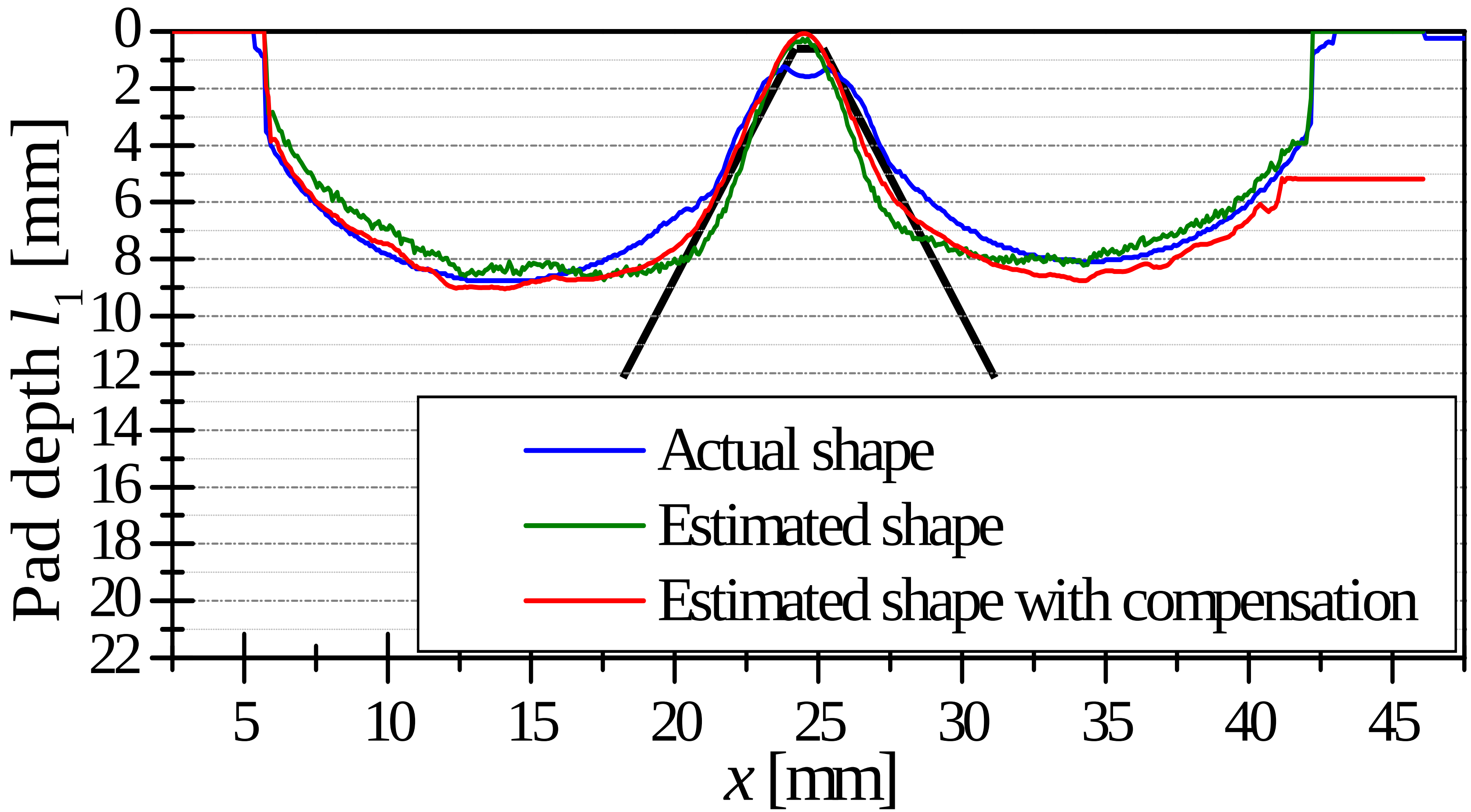
Limitation of Shape of Object

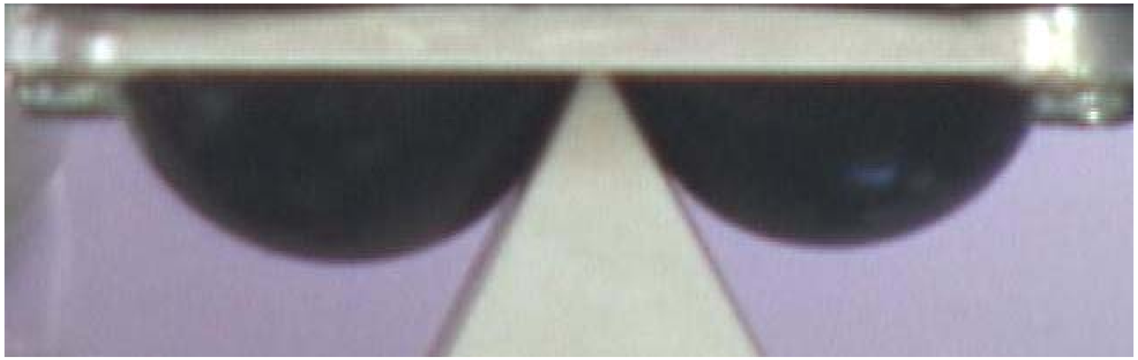




	Mean error [mm]	Standard deviation [mm]
Without compensation	0.67	0.62
With compensation	0.60	0.37

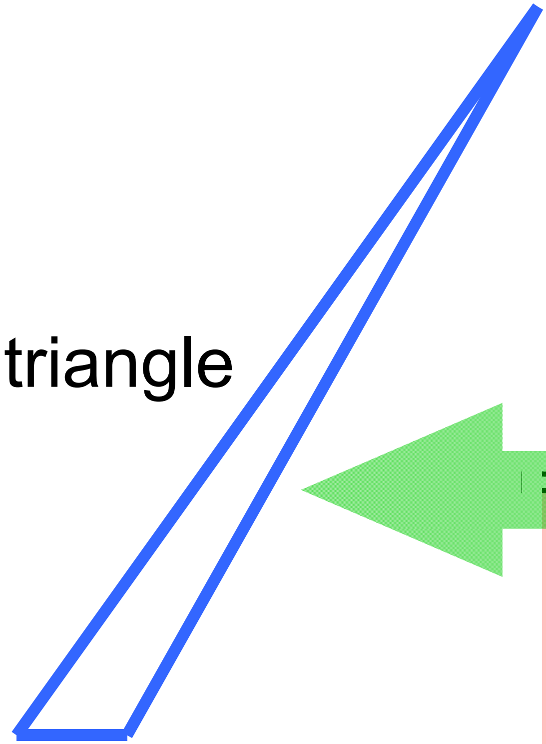
Limitation of Shape of Object

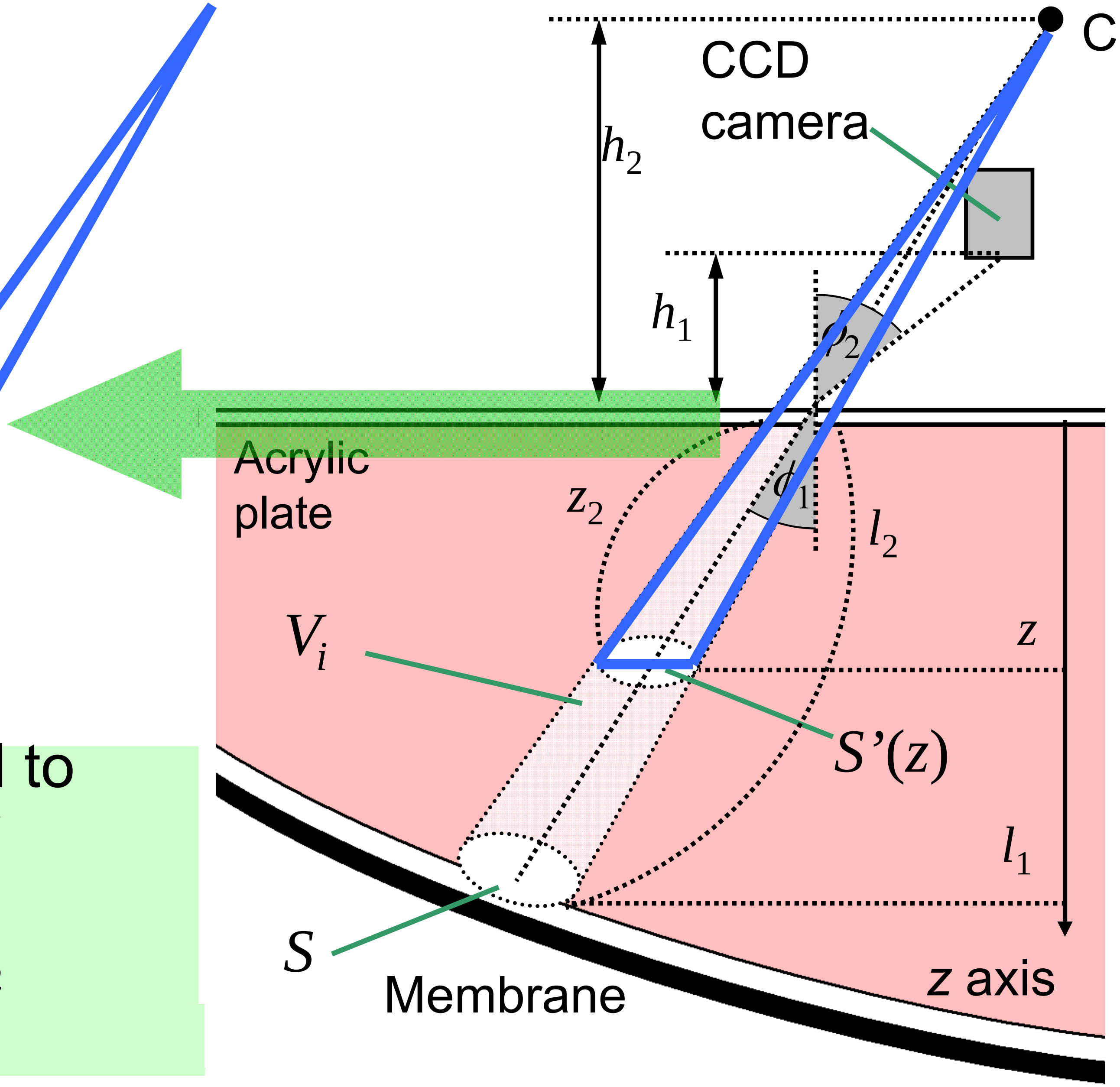




	Mean error [mm]	Standard deviation [mm]
Without compensation	0.74	0.54
With compensation	0.56	0.35

Calculation of Area $S'(z)$





$S'(z)$ is proportional to square of $(z+h_2)$.

$$S'(z) = s(z + h_2)^2$$

Calculation of Area $S'(z)$

$$S'(z) = s(z + h_2)^2$$

h_2 is obtained by these relations.

$$\Delta x \cong \frac{1}{\cos\phi_2}\left(2\Delta\phi_2 \cdot \frac{h_1}{\cos\phi_2}\right)$$

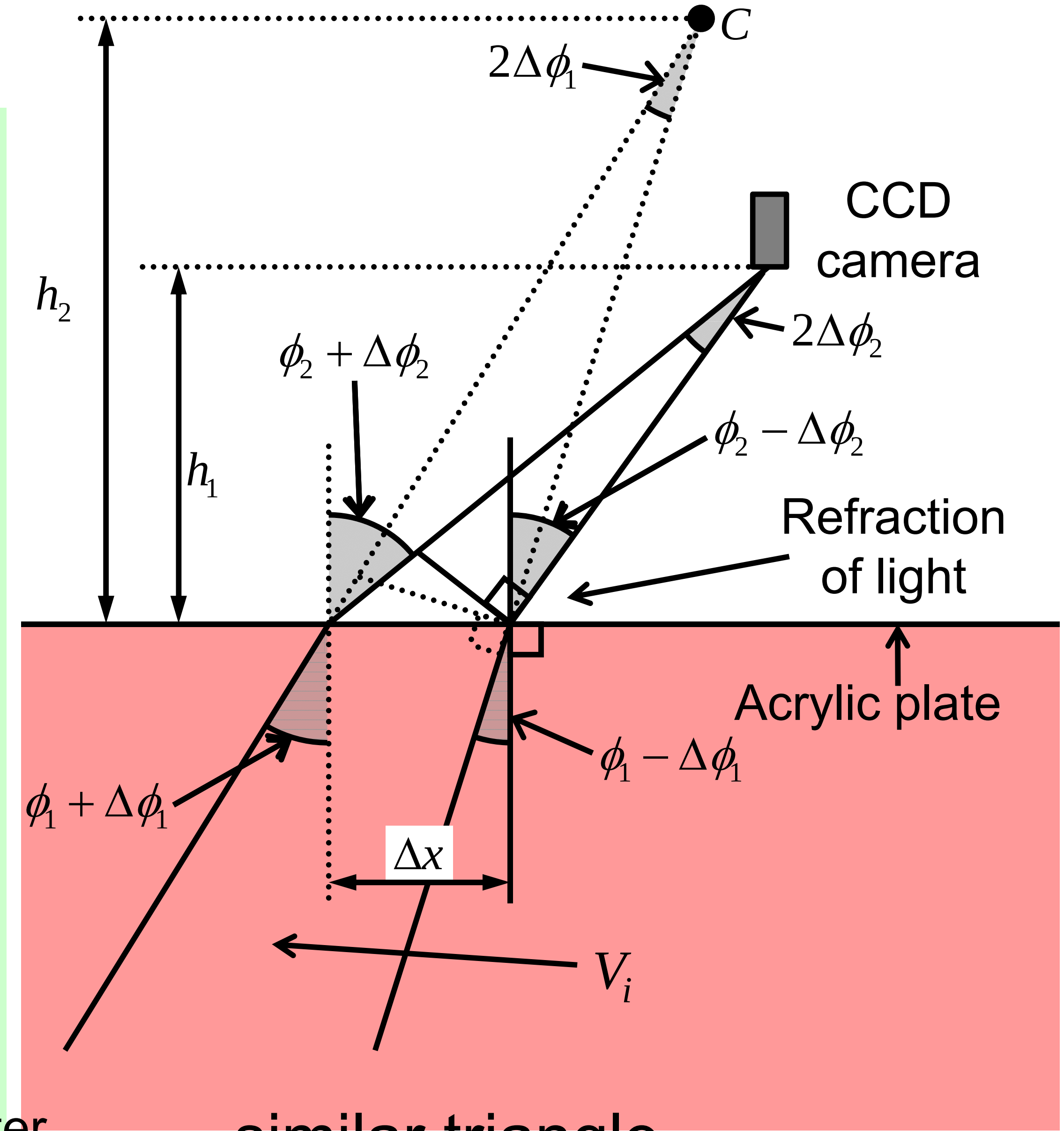
$$\cong \frac{1}{\cos\phi_1}\left(2\Delta\phi_1 \cdot \frac{h_2(\phi_2)}{\cos\phi_1}\right)$$

$$n_f = \frac{\sin(\phi_2 + \Delta\phi_2)}{\sin(\phi_1 + \Delta\phi_1)}$$

$$= \frac{\sin\phi_2 \cos\Delta\phi_2 + \cos\phi_2 \sin\Delta\phi_2}{\sin\phi_1 \cos\Delta\phi_1 + \cos\phi_1 \sin\Delta\phi_1}$$

$$\cong \frac{\sin\phi_2 + \Delta\phi_2 \cos\phi_2}{\sin\phi_1 + \Delta\phi_1 \cos\phi_1}$$

n_f : the relative refractive coefficient between the air and the colored water



similar triangle

Parameter Identification of c_R, c_G, κ

c_R, c_G, κ : 3 Unknown parameters

$$\frac{b_G \exp(c_G k l_1) - \kappa b_R \exp(c_R k l_1)}{Q_1(c_R)\{1-\exp(c_R k l_1)\} + Q_2(l_1, c_R)} = f\left(l_1(t_0), b_R(t_0), b_G(t_0)\right)$$

Preliminarily measured

$$\begin{cases} l_1(t_1), b_R(t_1), b_G(t_1) \\ l_1(t_2), b_R(t_2), b_G(t_2) \\ l_1(t_3), b_R(t_3), b_G(t_3) \end{cases}$$

Solving by numerical analytical approach such as Newton method

c_R, c_G and κ are set to 0.0290 mm^{-1}, 0.0336 mm^{-1} and 0.9924, respectively.

Parameter Identification of r, m_0, n

$$\psi_{sum}(x,y,t)=\sum_k \{\psi(x_k,y_k,t)-\psi(x_k,y_k,t_0)\} \quad \left(\sqrt{(x_k-x)^2+(y_k-y)^2}\le r\right)$$

$$m=m_0\exp[n\{l_1(x,y,t)-l_1(x,y,t_0)\}] \quad l_1'(x,y,t)=l_1(x,y,t)-m\,\psi_{sum}(x,y,t)$$

Comparing $l_1(x,y,t)-l_a(x,y,t)$ with $m\,\psi_{sum}(x,y,t)$

Transformed into double logarithmic equation l_a : actual depth

$$\ln\{l_1(x,y,t)-l_a(x,y,t)\}\equiv L$$

$$\ln\{m\,\psi_{sum}(x,y,t)\}=\ln\psi_{sum}(x,y,t)+\ln m_0+n\{l_1(x,y,t)-l_1(x,y,t_0)\}\equiv F$$

The least-square method (changing r from 1 to 50)

$$S=\sum(L-F)^2$$

r, m_0, and n are set to 0.000886 mm/rad, 30 pixel and 0.224 mm^{-1}.

Solving Equation for l_1

$$f\left(l_1(t), b_R(t), b_G(t)\right) = g(\phi_1) = f\left(l_1(t_0), b_R(t_0), b_G(t_0)\right)$$

$$f\left(l_1, b_R, b_G\right) = \frac{b_G \exp(c_G k l_1) - \kappa b_R \exp(c_R k l_1)}{Q_1(c_R)\{1 - \exp(c_R k l_1)\} + Q_2(l_1, c_R)}$$

We approximate l_1 by using bisection method.

$$l_{app}(t,1) = 0$$

$$l_{app}(t, i+1) = l_{app}(t, i) + \frac{l_{\max}}{2^i} \cdot f_{sig}(t, i+1)$$

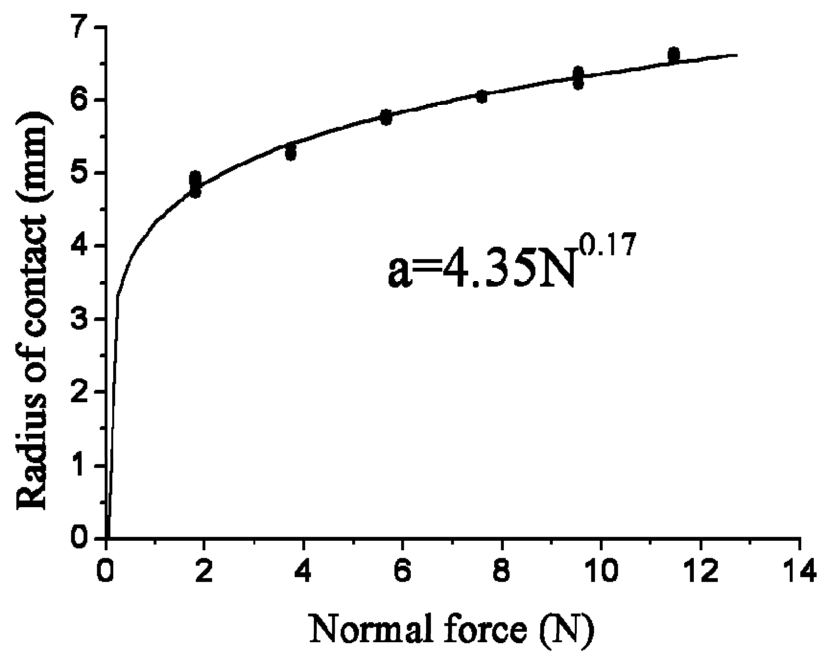
$$f_{sig}(t, i+1) = \begin{cases} 1 & \left(f\left(l_{app}(t,i), b_R(t), b_G(t)\right) \geq f\left(l_1(t_0), b_R(t_0), b_G(t_0)\right) \right) \\ -1 & \left(f\left(l_{app}(t,i), b_R(t), b_G(t)\right) < f\left(l_1(t_0), b_R(t_0), b_G(t_0)\right) \right) \end{cases}$$

$$l_1(t) \cong l_{app}(t, N)$$

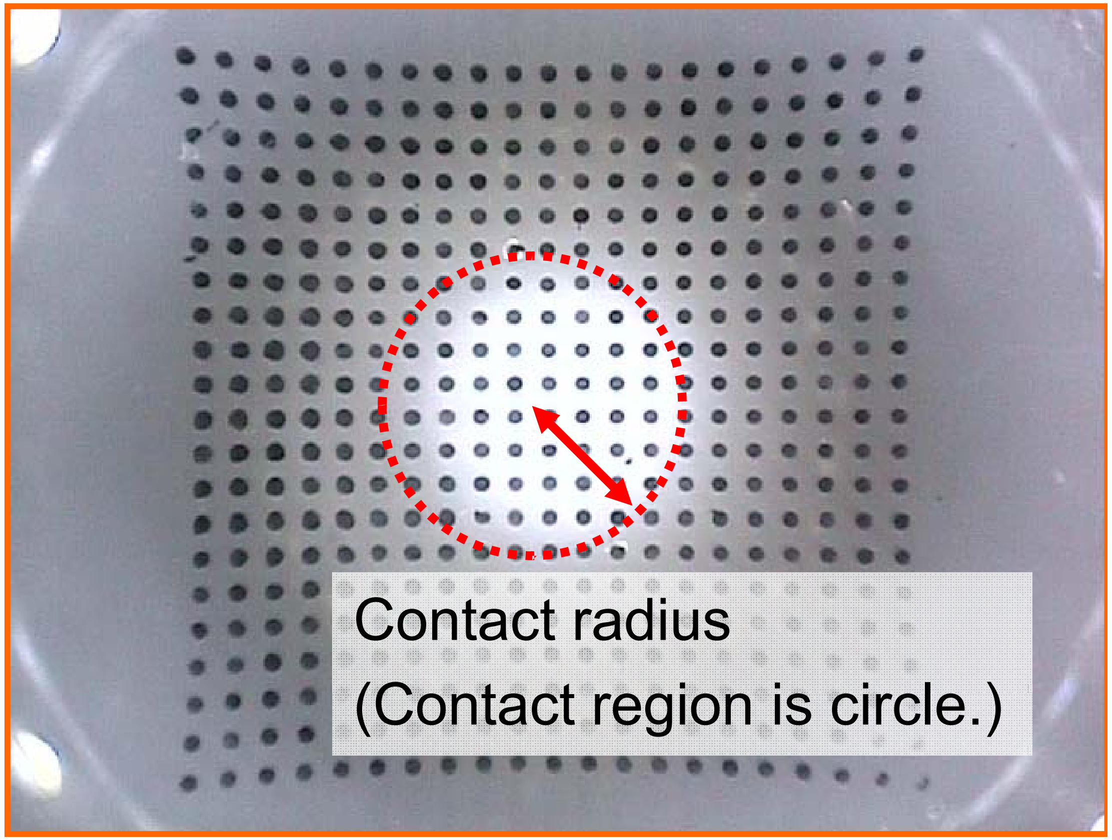
$l_{\max}$ and N are set to 14 mm and 16, respectively.

Measurement of Contact Force

- Normal force
- Tangential force
- Moment



Relation between normal force and contact radius

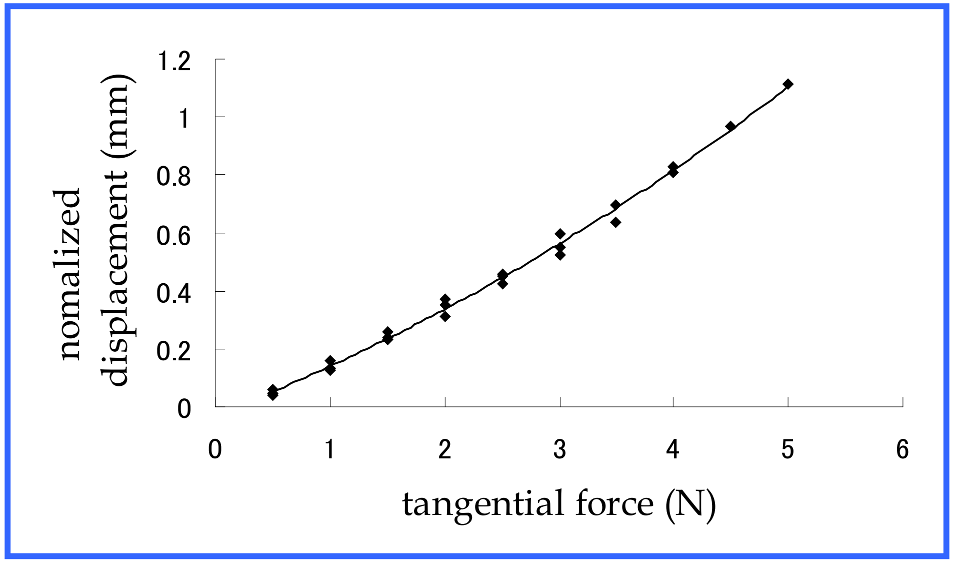


Refrence

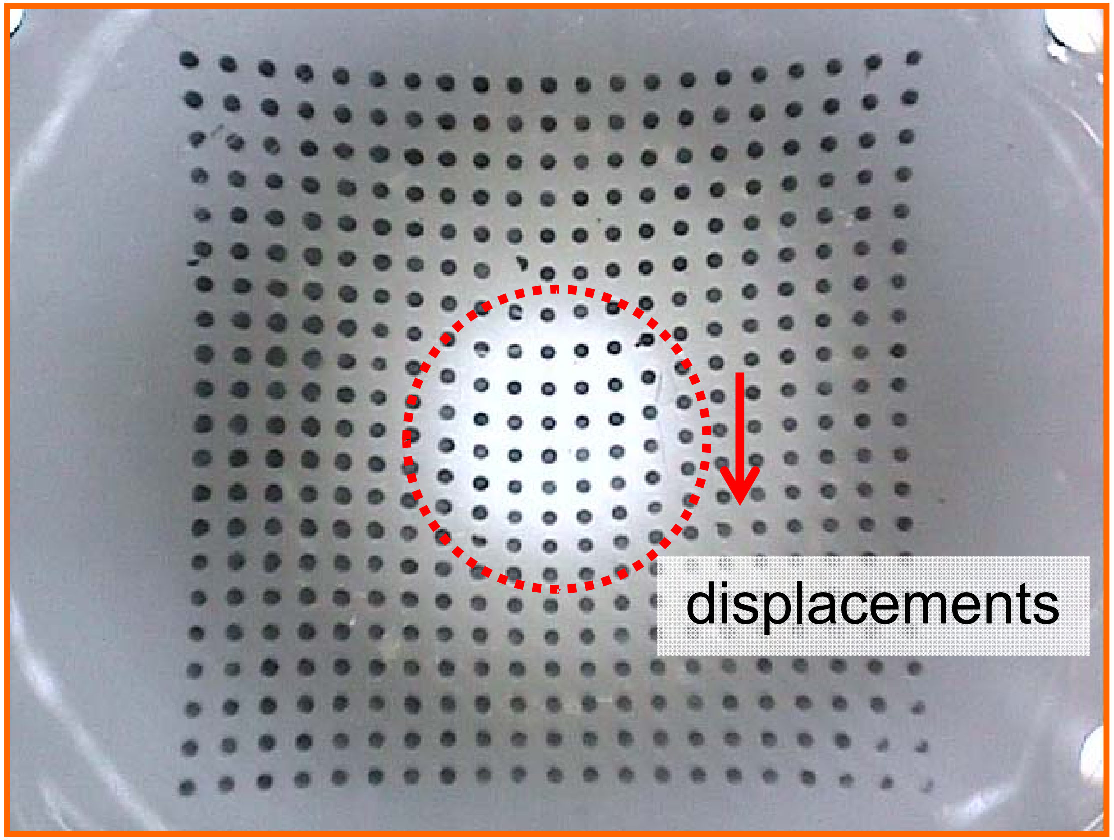
Xydas, Kao：Modeling of contact mechanics and friction limit surface for soft fingers in robotics with experimental results，International Journal of Robotics Research，Vol.18，No. 8，pp.941-950 (1999).

Measurement of Contact Force

- Normal force
- Tangential force
- Moment

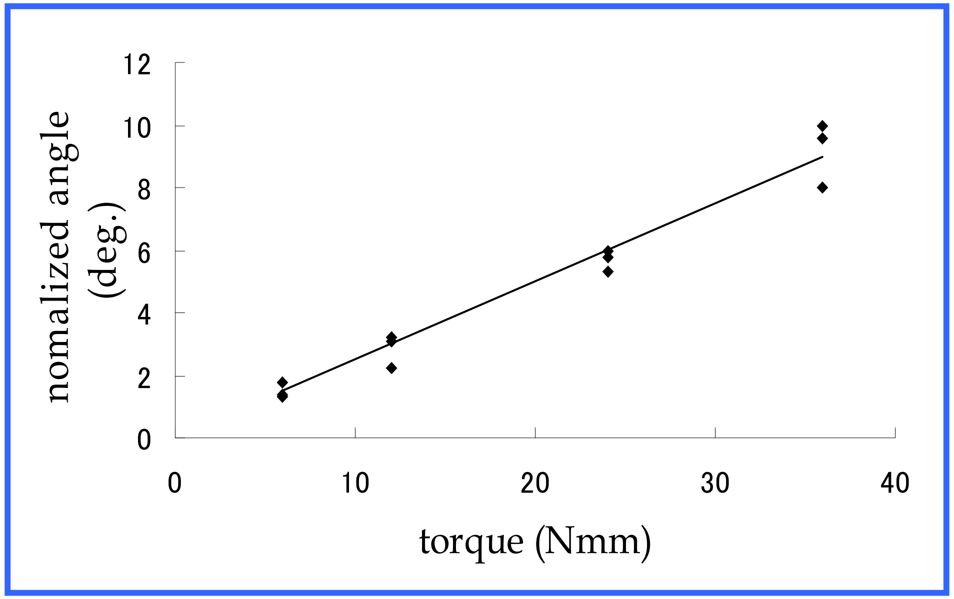


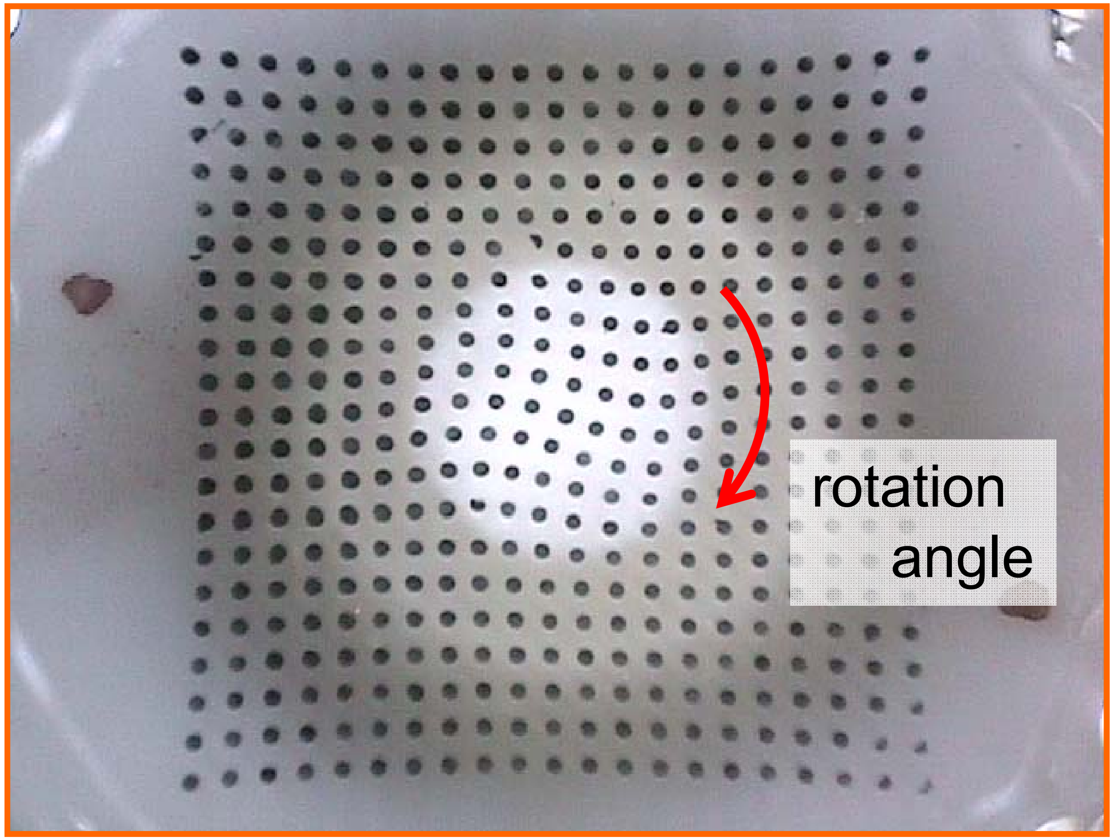
Relation between tangential force and displacements of dots



Measurement of Contact Force

- Normal force
- Tangential force
- Moment

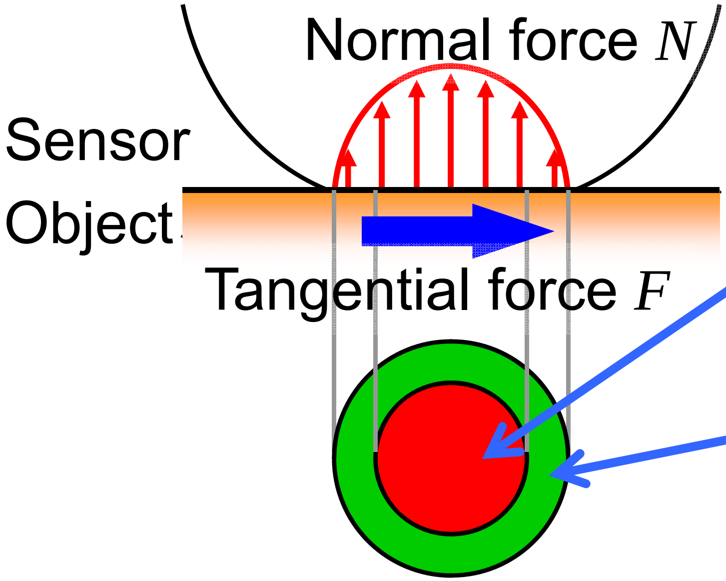




Relation between moment
and rotation angle of contact surface

Estimation of Slippage Degree

Partial slippage by non linear pressure distribution

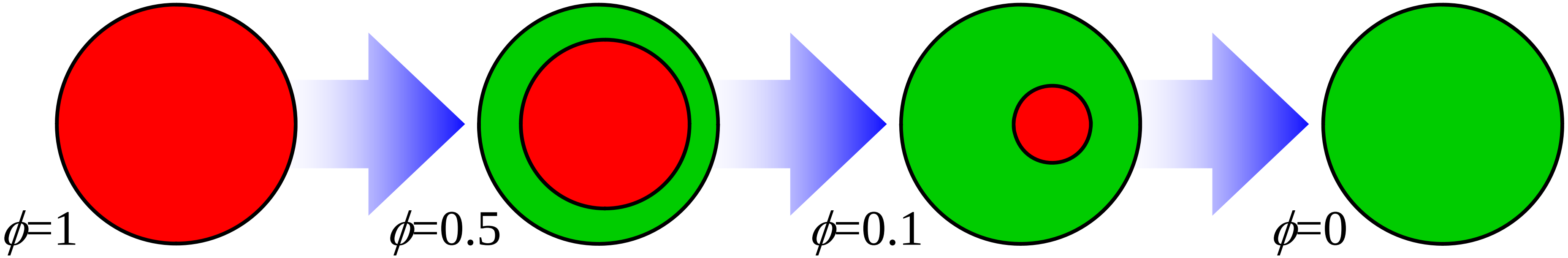


Contact region S_c

- Stick region S_s $\quad F<\mu N$
- Incipient slippage region $\quad F>\mu N$

Stick ratio $\phi = \dfrac{S_s}{S_c}$

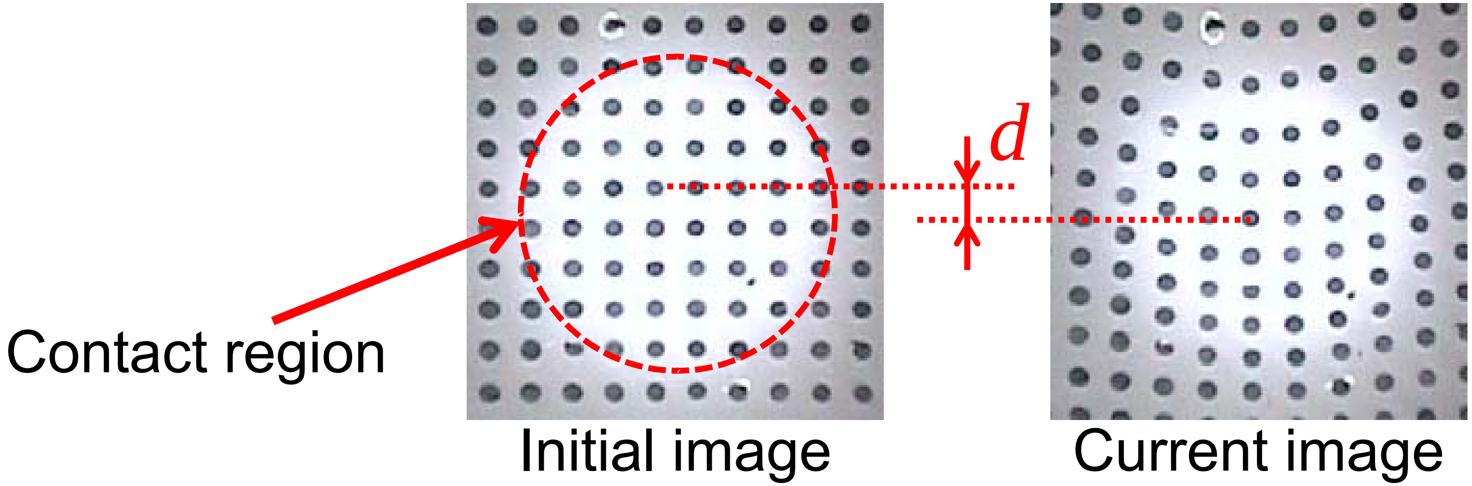
Stick ratio indicates slippage degree.



Keeping $\phi > 0$ → Preventing object from slipping

Stick Ratio Estimation Method

Discrimination of stick/slippage region



Displacement

d_k : Each dot

d_0 : Central dot ≒ Object

$\lvert d_0 - d_k \rvert < \delta$	In stick region
$\lvert d_0 - d_k \rvert > \delta$	In slippage region

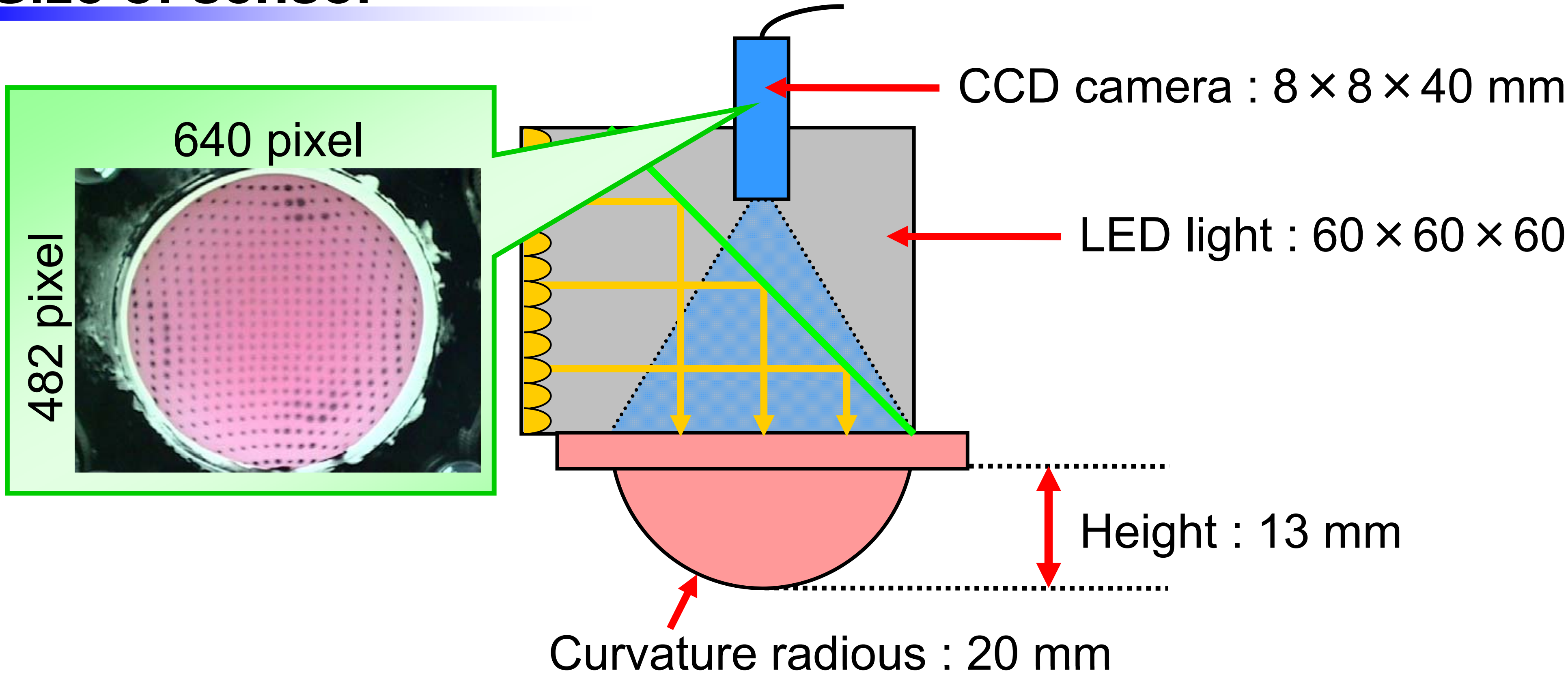
Stick ratio $\phi = \dfrac{S_s}{S_c} \cong \dfrac{N_s}{N_c}$

N_s : Number of dots in stick region

N_c : Number of dots in contact region

Forecasted Question

Size of sensor



Thickness of membrane : 1 mm

Processing speed

The processing speed depends on spec of PC.
Although the processing speed is about 1Hz currently, we can process the method faster by using high spec PC in the future.

Forecasted Question

- 水平方向の分解能は？
- どれくらいの形状まで測れるの？
- 接触領域内しか推定できないんじゃないの？
- 接触領域はどうやって推定するの？
- 何故赤色にしたの？
- 液体じゃないと駄目なの？
- 同軸照明じゃないと駄目なの？
- なぜシリコーンゴム？
- 膜の厚みはどう影響する？
- Vision-based 以外のセンサってどんなのがあるの？electrical resistance, capacitance, electromagnetic component, piezoelectric/ ultrasonic/ component, strain gauge

Forecasted Question

- 接触領域内しか推定できないんじゃないの？

  Although we can estimate the entire shape of the touch pad, the estimation of the object shape is confined to the contact region. Therefore, the estimation of the contact region is also important.

- 接触領域はどうやって推定するの？

  We can estimate the contact region by using the shape of the touch pad.

  We will present the method to estimate the contact region at the IEEE international conference IROS in October.

- 何故赤色にしたの？

  We can estimate if we use blue or green water. However, If we use the other colored water, it is difficult to estimate, because we want to eliminate the two scattering coefficient by approximation. And the resolution depends on the difference between cR and cG. Therefore, it is desirable that cR is small and cG is large.

- なぜシリコーンゴム？

  The silicon rubber is hardly influenced by the environment.

Forecasted Question

- Vision-based 以外のセンサってどんなのがあるの？

  electrical resistance, capacitance, electromagnetic component, piezoelectric/ ultrasonic/ component, strain gauge.

- 分解能は？

  The resolution of bR and bG are 0.001 (0~255 value) by using smoothing (filter mask is 29×29 pixel).

  When depth changes 11.7 mm, bR and bG changes 8 and 31.5.

  Therefore, the resolution of depth is about 11.7/(31.5/0.001)=0.00037 [mm].

  However the actual resolution is not determined because of nonlinearity.

- @@@@

Theory for Intensity of Light

Sum of light intensity I_{sum} in region V_i

$$I_{sum} = SR_1(\theta, b)R_2 I_0 \exp(-ckl_1) + sR_1'(\phi_1)R_2 I_0 \begin{bmatrix} \{1-\exp(-ckl_1)\}Q_1(c) \\ -\exp(-ckl_1)Q_2(l_1, c) \end{bmatrix}$$

Geometrical relationship

$$S'(z) = s(z + h_2)^2$$

(Detail is abbreviated.)

s : Proportional constant h_2 : Obtained from h_1

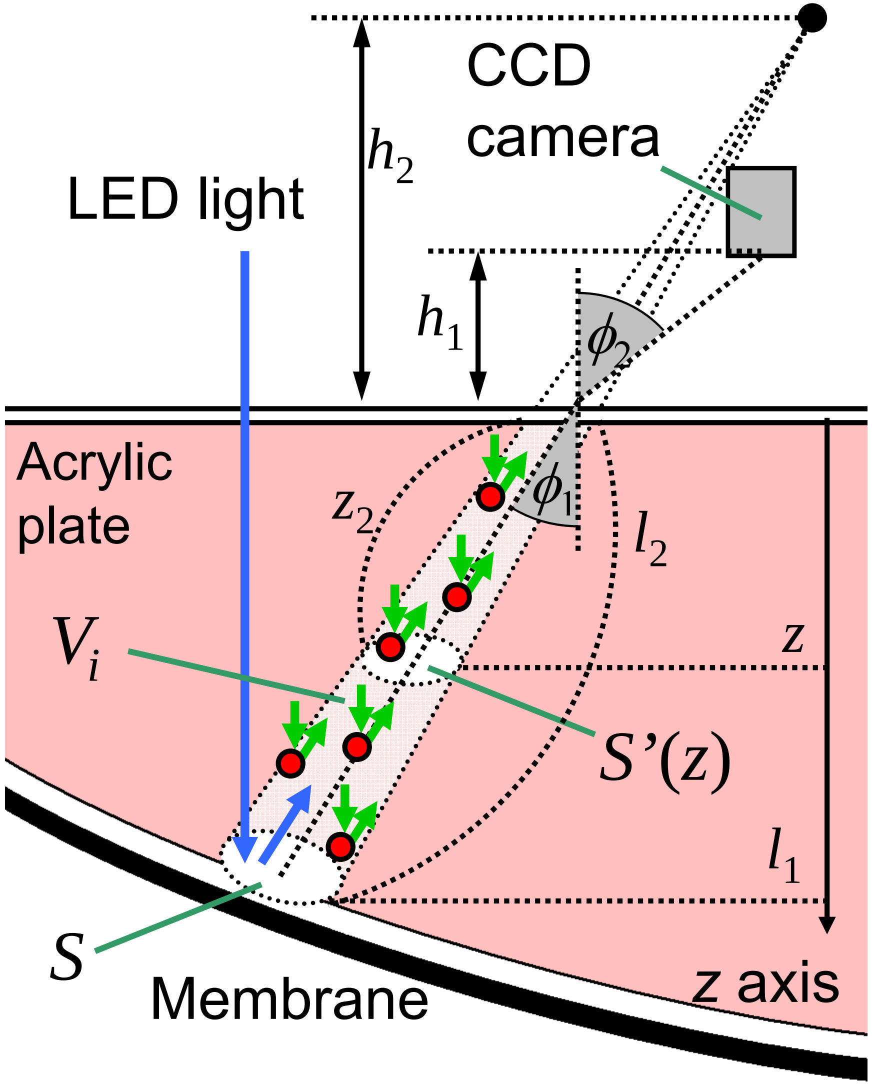
Definition of parameter

$$kl_1 = l_1 + l_2$$

$$k = 1 + \frac{1}{\cos\phi_1}$$

$$Q_1(c) = \frac{h_2^2}{k} + \frac{2h_2}{ck^2} + \frac{2}{c^2k^3}$$

$$Q_2(l_1, c) = \frac{l_1^2 + 2h_2 l_1}{k} + \frac{2l_1}{ck^2}$$



Modification of Equation

Substitution of RGB values in the image

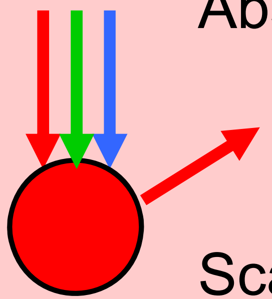
$$I_{sum} = SR_1(\theta,b)R_2 I_0 \exp(-ckl_1) + sR_1'(\phi_1)R_2 I_0 \left[\begin{array}{l} Q_1(c)\{1-\exp(-ckl_1)\} \\ -Q_2(l_1,c)\exp(-ckl_1) \end{array} \right]$$

I_{sum} ← b_R/β_R, b_G/β_G, b_B/β_B

I_0 ← $\alpha_R I_0$, $\alpha_G I_0$, $\alpha_B I_0$

c : Extinction coefficient ← c_R, c_G, c_B

$R_1'(\phi_1)$ ←



Absorbed: $R'_{G1}(\phi_1) \cong 0$, $R'_{B1}(\phi_1) \cong 0$

Scattered: $R'_{R1}(\phi_1) > 0$

$\alpha_R, \alpha_G, \alpha_B, \beta_R, \beta_G, \beta_B$: Propotional constants

b_R, b_G, b_B:RGB values in image

$$b_R = SR_1(\theta,b)R_2\alpha_R\beta_R I_0 \exp(-c_R k l_1) + sR'_{R1}(\phi_1)R_2\alpha_R\beta_R I_0\left[Q_1(c_R)\{1-\exp(-c_R k l_1)\} - Q_2(l_1,c_R)\exp(-c_R k l_1)\right]$$

$$b_G = SR_1(\theta,b)R_2\alpha_G\beta_G I_0 \exp(-c_G k l_1)$$

$$b_B = SR_1(\theta,b)R_2\alpha_B\beta_B I_0 \exp(-c_B k l_1)$$

Modification of Equation

Elimination of $R_1(\theta, b)$ depending θ and b

$$b_R = SR_1(\theta, b)R_2 I_0 \alpha_R \beta_R \exp(-c_R k l_1) + sR'_{R1}(\phi_1)R_2 I_0 \alpha_R \beta_R \begin{bmatrix} Q_1(c_R)\{1-\exp(-c_R k l_1)\} \\ -Q_2(l_1, c_R)\exp(-c_R k l_1) \end{bmatrix}$$

$$b_G = SR_1(\theta, b)R_2 I_0 \alpha_G \beta_G \exp(-c_G k l_1)$$

θ : Angle of membrane

b : Color of inner membrane

Solving simultaneous equations

$$b_G = \begin{bmatrix} \kappa b_R \exp(c_R k l_1) \\ + g(\phi_1)\{Q_1(c_R)\{1-\exp(ckl_1)\} + Q_2(l_1, c_R)\} \end{bmatrix} \exp(-c_G k l_1)$$

$$\kappa = \frac{\beta_G \alpha_G}{\alpha_R \beta_R}$$

$$g(\phi_1) = \alpha_G \beta_G s R_2 R'_{R1}(\phi_1) I_0$$

Modification of Equation

Equation to obtain pad depth l_1 from color intensities b_R, b_G

$$b_G = \begin{bmatrix} \kappa b_R \exp(c_R k l_1) \\ + g(\phi_1)\{Q_1(c_R)\{1-\exp(ckl_1)\} + Q_2(l_1, c_R)\} \end{bmatrix} \exp(-c_G k l_1)$$

Solving for $g(\phi_1)$

$$g(\phi_1) = \frac{b_G \exp(c_G k l_1) - \kappa b_R \exp(c_R k l_1)}{Q_1(c_R)\{1-\exp(c_R k l_1)\} + Q_2(l_1, c_R)}$$

$$= const$$

$$\equiv f(l_1, b_R, b_G)$$

ϕ_1 : Calculated from position of P_i

k, h_2 : Obtained from ϕ_1, h_1

c_R, c_G, κ : Preliminarily calculated (abbreviation)

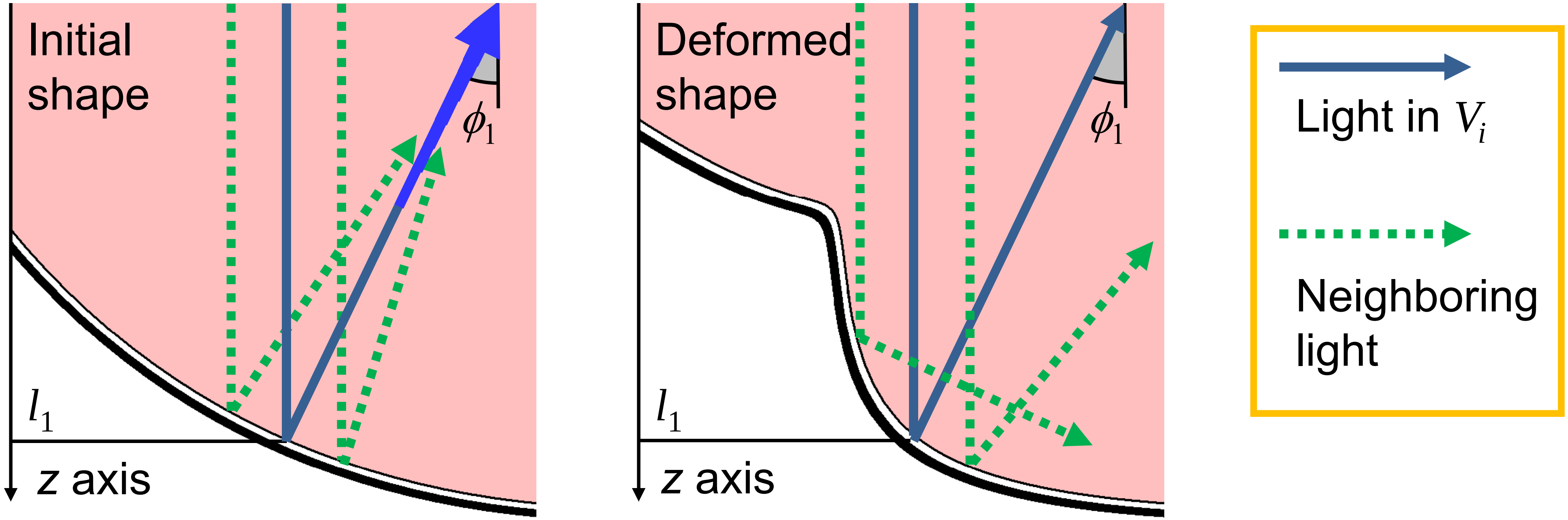
Relation between pad depth l_1 and color intensities b_R, b_G

$$f(l_1(t), b_R(t), b_G(t)) = g(\phi_1) = f(l_1(t_0), b_R(t_0), b_G(t_0))$$

$l_1(t_0)$, $b_R(t_0)$, $b_G(t_0)$: Preliminarily measured

Compensating Approximation Error

Effect of neighboring light



Neighboring light increases light intensity in V_i.

Neighboring light travels in different direction.

➡ Error of l_1 depends on shape of membrane and pad depth.

Equation to compensate depth l_1 (Detail is abbreviated.)

$$l_1' = l_1 - m\psi_{sum}$$

l'_1 : Compensated depth

ψ_{sum} : Function of shape of membrane

m : Function of pad depth

Acquisition of Tactile Information by Vision-based Tactile Sensor for Dexterous Handling of Robot Hands

Table of Contents

Background

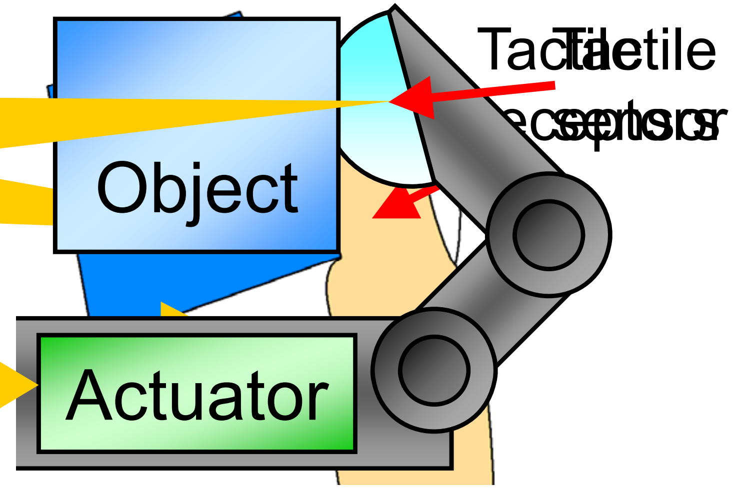
Dexterous handling of object by robot hand

Tactile information

- Contact force
- Slippage
- Shape/irregularity
- Temperature etc…

Sense

Feed back



Requirement of tactile sensors

Simultaneous acquisition of many types of tactile information → multifunctional/compact robot hand

Many sensors and other conventional devices…

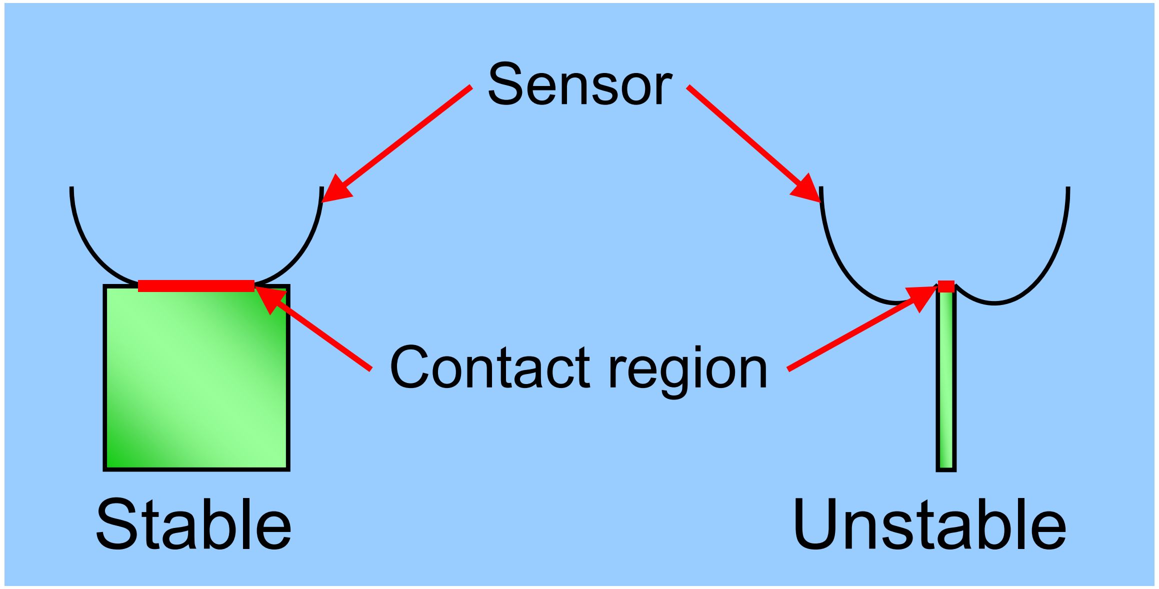
- can obtain only single type of tactile information.
- cannot obtain
  1. contact region on sensor
  2. location of contacted object

Our method can obtain even if shape/movement of object are complex.

Purpose

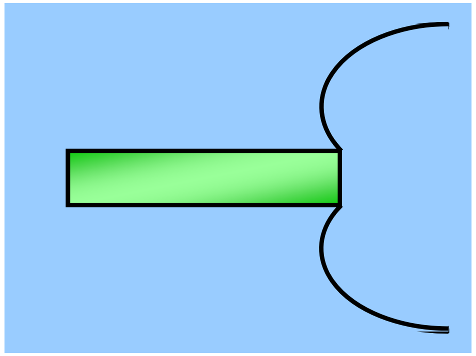
Contact region on sensor allows to...

- evaluate grasp task stability
- estimate object shape in accurate manner
- evaluate contact pressure



Location of contacted object is needed because...

- manipulation tasks require exact position/angle of object
- deformation of elastic sensor body makes object location uncertain

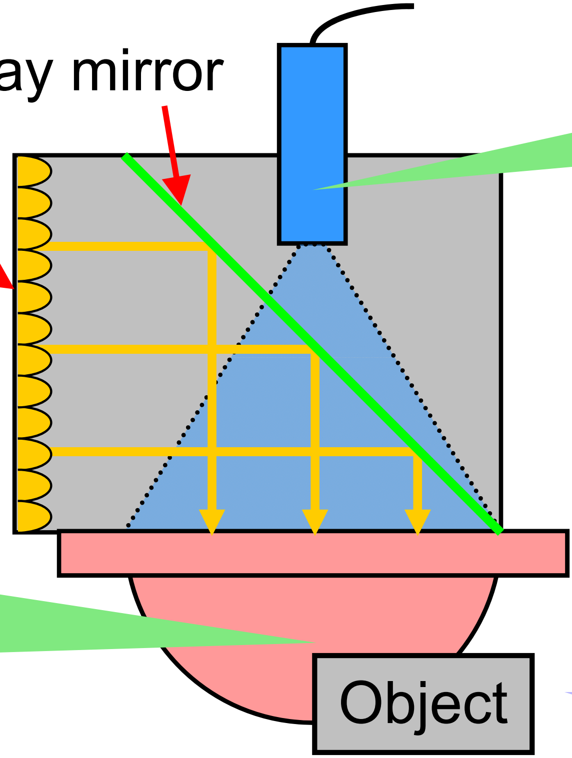


Purpose

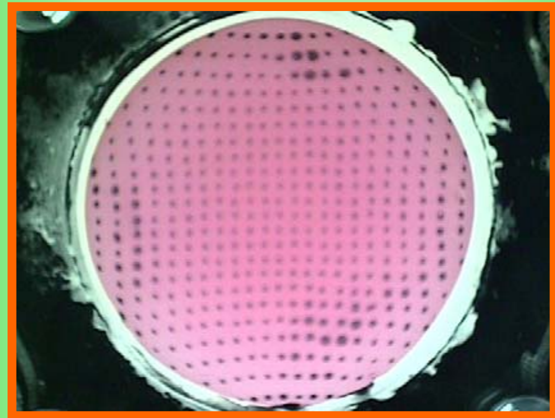
Efficient method to Acquire contact region and location of object

Table of Contents

Structure of Vision-Based Tactile Sensor

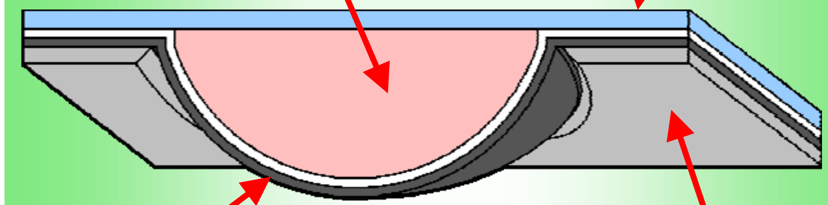


CCD camera



Analysis of
- dot positions
- color intensity

Touch pad



Two-layered elastic membranes
- Outer : Black color
- Inner : White color, Printed dotted pattern

Acquisition of tactile information

- Contact force*
  (normal, tangential, moment)
- Degree of slippage**
- Shape/irregularity of object

*:G. Obinata (*Mobile Robots: Perception & Navigation*, 2007), **:Y. Ito (*IEEE SENSORS*, 2009)

Shape-sensing Method by Our Proposed Sensor

Principle of shape-sensing method***

***:Y. Ito (*IEEE CASE*, 2010)

Significant relationship

Depth of touch pad

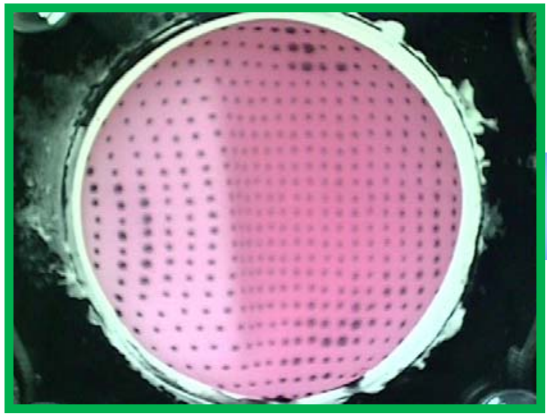
⬍ Dependency

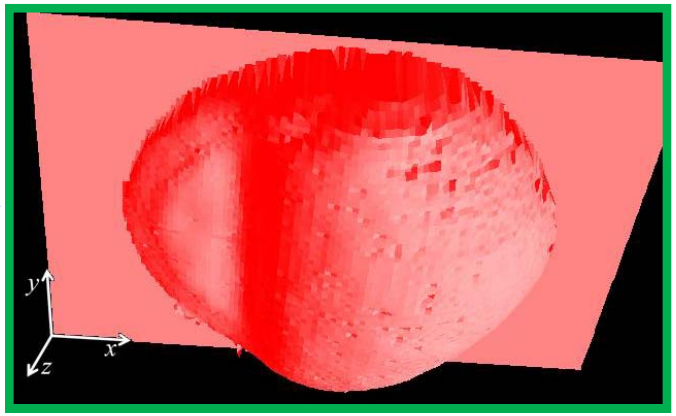
Light intensity in V_i (Input signal of CCD)

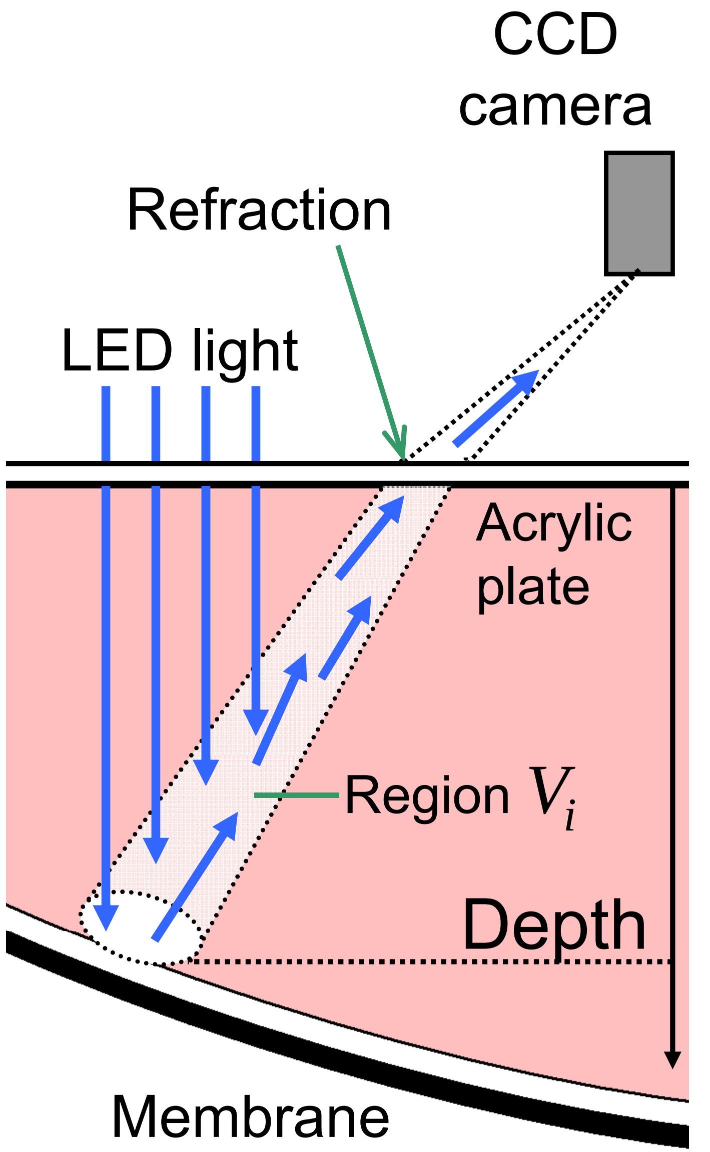
⬍ Proportionality

Color intensities (RGB values)

Calculation of pad shape from RGB values.





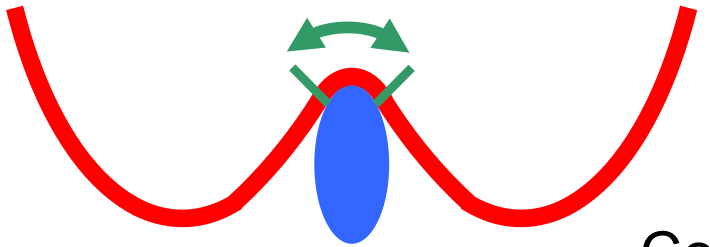


Shape-sensing method is used in this study.

Table of Contents

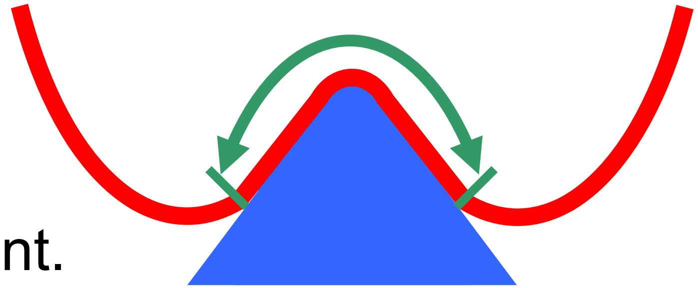
Theory of Contact Region Estimation

Difficulty to estimate contact region from shape information

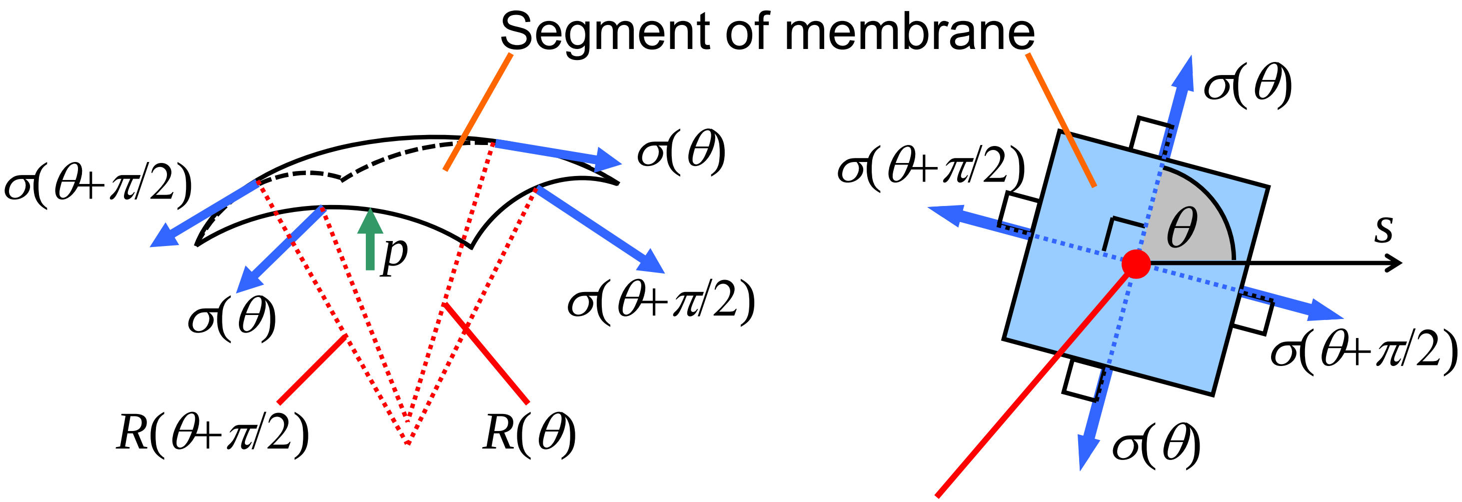


Pad shapes are similar.

Contact regions are different.



Analysis of small segment of membrane



p : inner pressure

σ : tensional forces per unit length

R : curvature radius

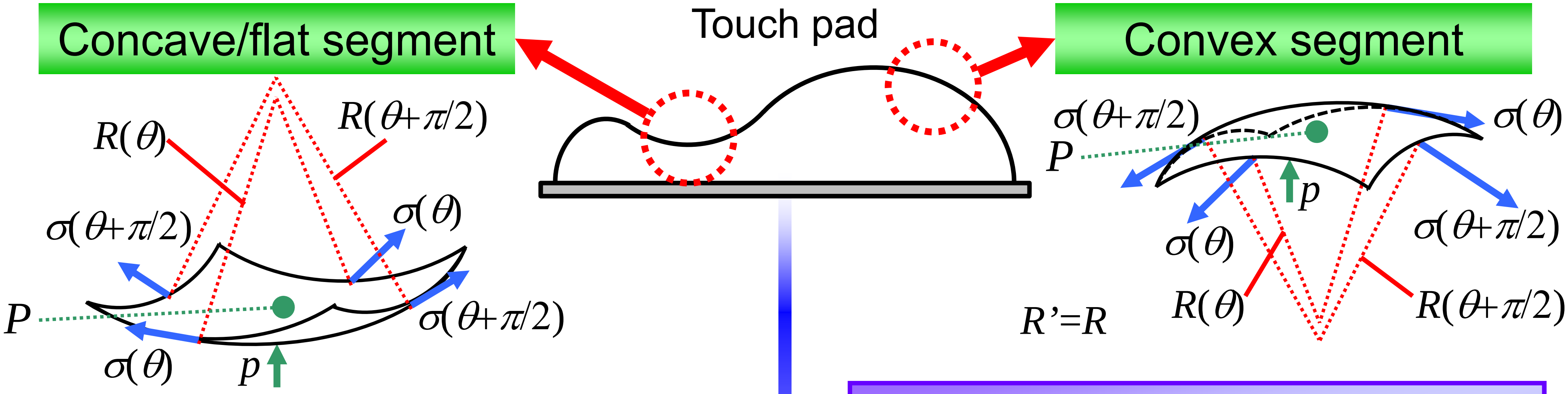
Definition : $R' = R$

Center of segment P

Equilibrium equation of segment $$\frac{\sigma(\theta)}{R'(\theta)} + \frac{\sigma(\theta+\pi/2)}{R'(\theta+\pi/2)} = p \quad \left(0 \le \theta < \frac{\pi}{2}[\mathrm{rad}]\right)$$

Theory of Contact Region Estimation

Curvature radius of small segment



$R' = -R$ ⇒ $\frac{1}{R'} \le 0$ $\begin{cases} \sigma \ge 0 \\ p \ge 0 \end{cases}$

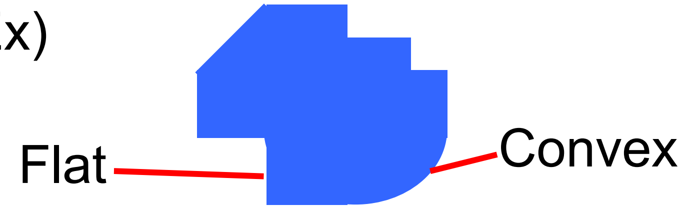
$$\frac{\sigma(\theta)}{R'(\theta)} + \frac{\sigma(\theta+\pi/2)}{R'(\theta+\pi/2)} = p$$ Not satisfied

$1/R' \le 0$ ⇒ P is in contact region

$R' = R$

Assumption :
Object surfaces are convex/flat.

Ex)



$1/R' > 0$ ⇒ P is in non-contact region

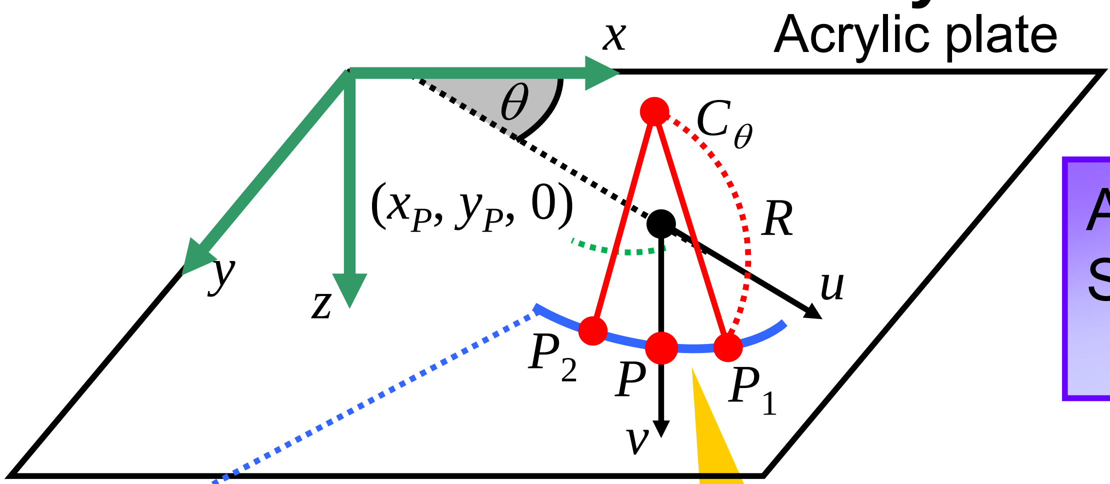
Necessary and sufficient condition for P to belong to contact region $\frac{1}{R'(\theta)} \le 0 \quad (0 \le \theta < \pi\,[\mathrm{rad}])$

Calculation of Curvature Radius

Curvature radius defined by three reference points

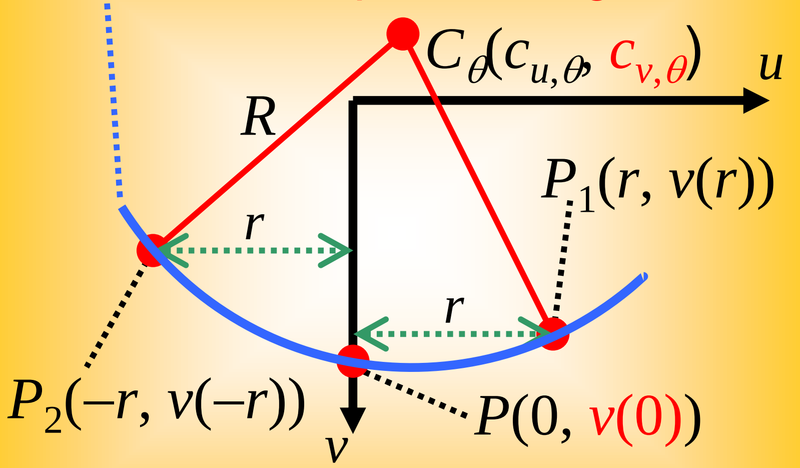
u-v plane : perpendicular to x-y plane

$(x_P, y_P, 0)$: origin of u-v coordinate



Assumption :
Shape of segment around P is spherical in u-v plane.

Pad shape : obtained by shape-sensing method



r : constant parameter

$v(u)$: v value at u

Substituting 3 reference points P, P_1, P_2

$$(u - c_{u,\theta})^2 + (v - c_{v,\theta})^2 = R(x_P, y_P, \theta)^2$$

Discrimination of convex/concave shape

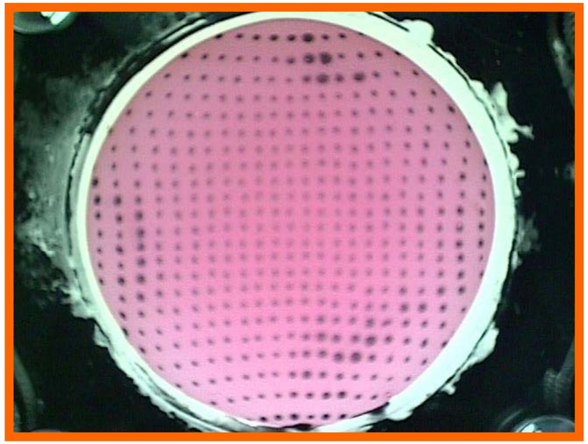
$$R' = \begin{cases} |R| & (v(0) \geq c_{v,\theta}) \\ -|R| & (v(0) < c_{v,\theta}) \end{cases}$$

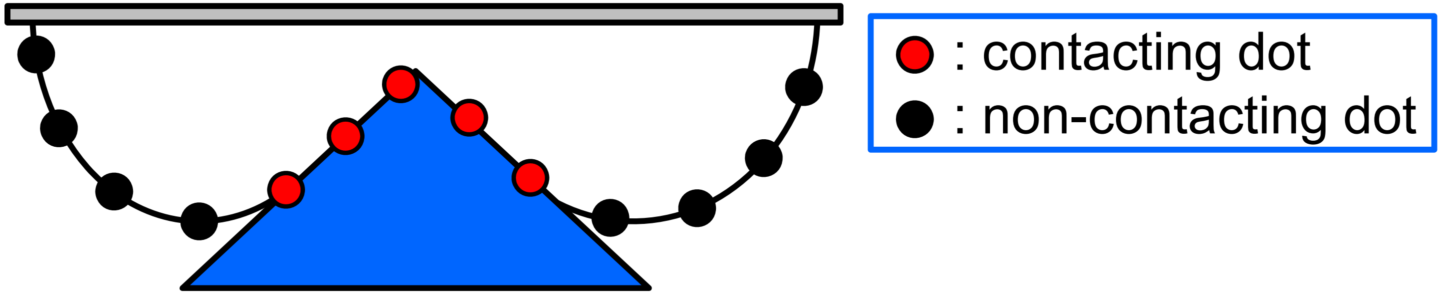
Calculation of R of all segments in various u-v planes

Table of Contents

Estimation of Object Position

Analysis of dots painted on sensor surface

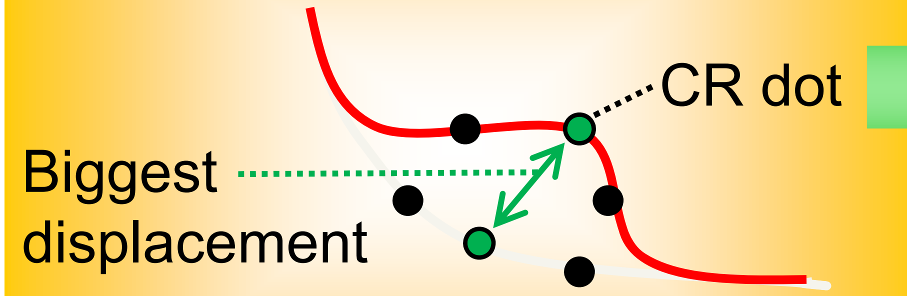




Contacting dots move/rotate with object.

Contact reference dot (CR dot) is always in contact.

CR dot : whose displacement from initial position is biggest.



When CR dot doesn't slip to object,

Object's		CR dot's
displacement	=	displacement
rotation angle	=	rotation angle

Dot's positions/displacements are calculated by shape-sensing method.

Estimation of Object Orientation

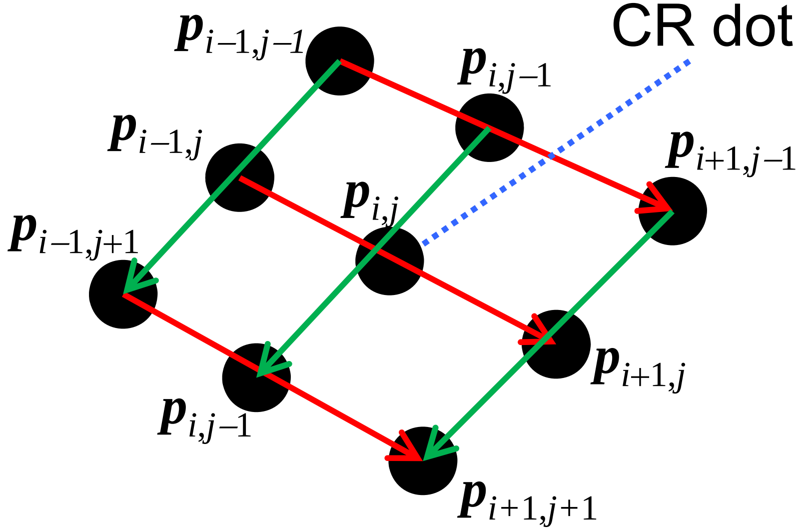
Rotation angle of CR dot are obtained from rotation matrix R

3 basis vectors $\boldsymbol{n}_1$, $\boldsymbol{n}_2$ and $\boldsymbol{n}_3$ around CR dot

$$\boldsymbol{n}_1 = \boldsymbol{q}_1 / |\boldsymbol{q}_1| \qquad \boldsymbol{n}_2 = \boldsymbol{q}_2 / |\boldsymbol{q}_2| \qquad \boldsymbol{n}_3 = \boldsymbol{n}_1 \times \boldsymbol{n}_2$$

$$\boldsymbol{q}_1 = \sum_{k=-1}^{1} \left(\boldsymbol{p}_{i+1,\,j+k} - \boldsymbol{p}_{i-1,\,j+k} \right)$$: average of ← (red)

$$\boldsymbol{q}_2 = \sum_{k=-1}^{1} \left(\boldsymbol{p}_{i+k,\,j+1} - \boldsymbol{p}_{i+k,\,j-1} \right)$$: average of ← (green)



$\boldsymbol{p}_{i,j}$: position of dot (i-th from left and j-th from top)

Assumption : Eight dots adjacent to CR dot are in contact with object.

⇒ Positional relation of nine dots is not changed.

$$\begin{bmatrix} \boldsymbol{n}_1^n \\ \boldsymbol{n}_2^n \\ \boldsymbol{n}_3^n \end{bmatrix} = {}^m\boldsymbol{R}^n \begin{bmatrix} \boldsymbol{n}_1^m \\ \boldsymbol{n}_2^m \\ \boldsymbol{n}_3^m \end{bmatrix}$$

${}^m\boldsymbol{R}^n$: rotation matrix from m to n

m, n : sampling index

Estimation of Object Orientation

Divide of rotation angle

$$ {}^{m}\boldsymbol{R}^{n} = {}^{m}\boldsymbol{R}^{n}_{z}\,{}^{m}\boldsymbol{R}^{n}_{y}\,{}^{m}\boldsymbol{R}^{n}_{x} $$

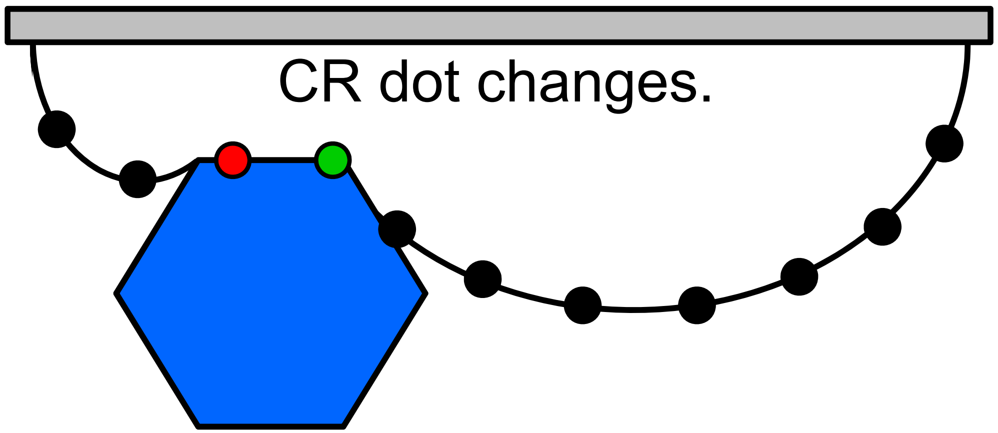
Obtain

$$ {}^{m}\theta^{n}_{z},\ {}^{m}\theta^{n}_{y},\ {}^{m}\theta^{n}_{x} $$

${}^{m}\boldsymbol{R}^{n}_{x}$, ${}^{m}\boldsymbol{R}^{n}_{y}$, ${}^{m}\boldsymbol{R}^{n}_{z}$: rotation matrix around *x*, *y*, *z*-direction

${}^{m}\theta^{n}_{x}$, ${}^{m}\theta^{n}_{y}$, ${}^{m}\theta^{n}_{z}$: rotation angle around *x*, *y*, *z*-direction

Consideration of change of CR dot



- ● (green) : CR dot
- ● (red) : contacting dot
- ● (black) : non-contacting dot

Not satisfied

$$ {}^{m}\theta^{n}_{obj\,x} = {}^{m}\theta^{n}_{x} $$

$$ {}^{m}\theta^{n}_{obj\,y} = {}^{m}\theta^{n}_{y} $$

$$ {}^{m}\theta^{n}_{obj\,z} = {}^{m}\theta^{n}_{z} $$

${}^{m}\theta^{n}_{obj}$: rotation angle of object

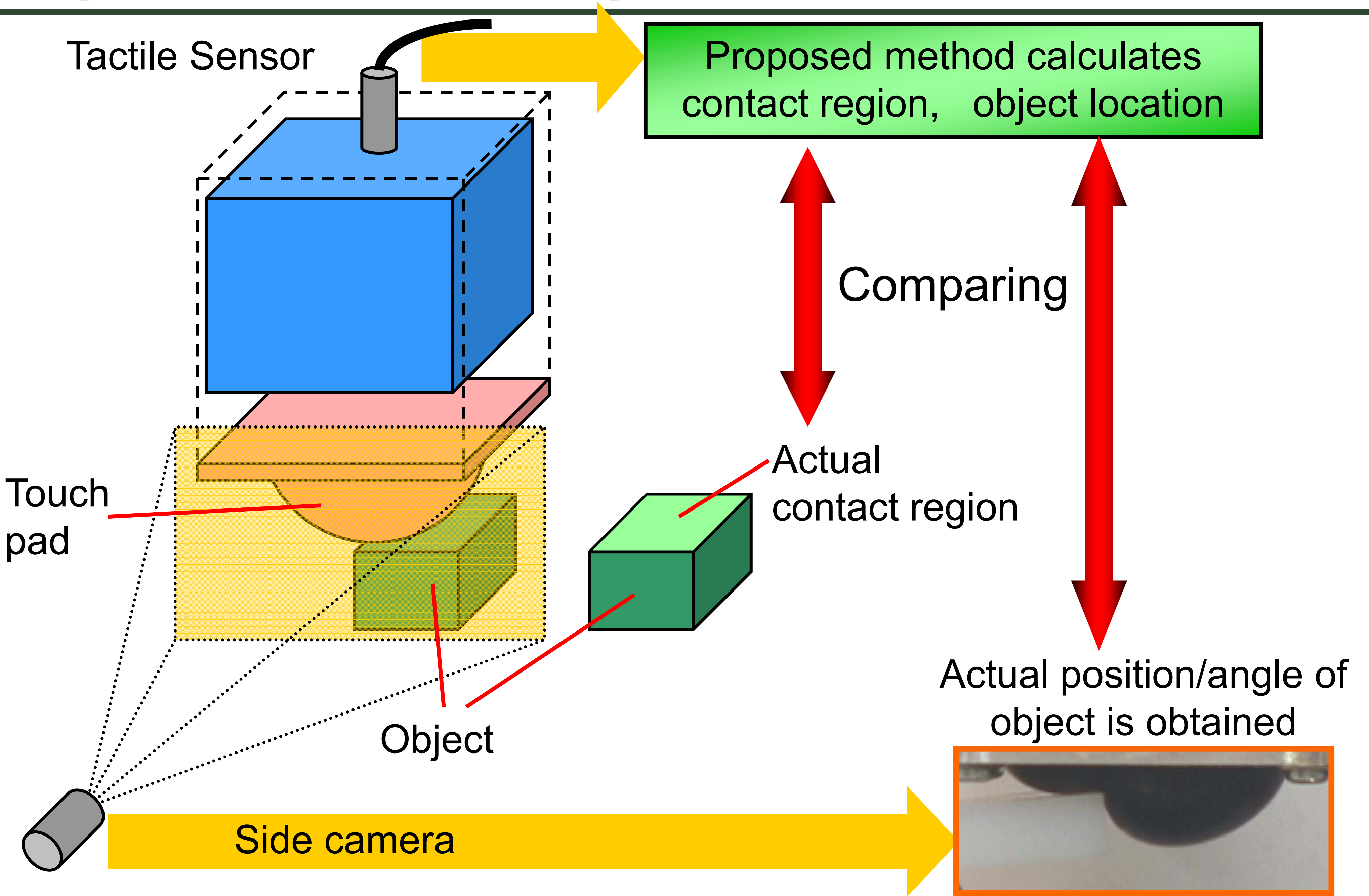
Rotation angles of object = Sums of rotation angles of CR dot at each step

$$ {}^{m}\theta^{n}_{obj\,x} = \sum_{k=m}^{n-1} {}^{k}\theta^{k+1}_{x},\quad {}^{m}\theta^{n}_{obj\,y} = \sum_{k=m}^{n-1} {}^{k}\theta^{k+1}_{y},\quad {}^{m}\theta^{n}_{obj\,z} = \sum_{k=m}^{n-1} {}^{k}\theta^{k+1}_{z} $$

(when CR dot doesn’t slip to object)

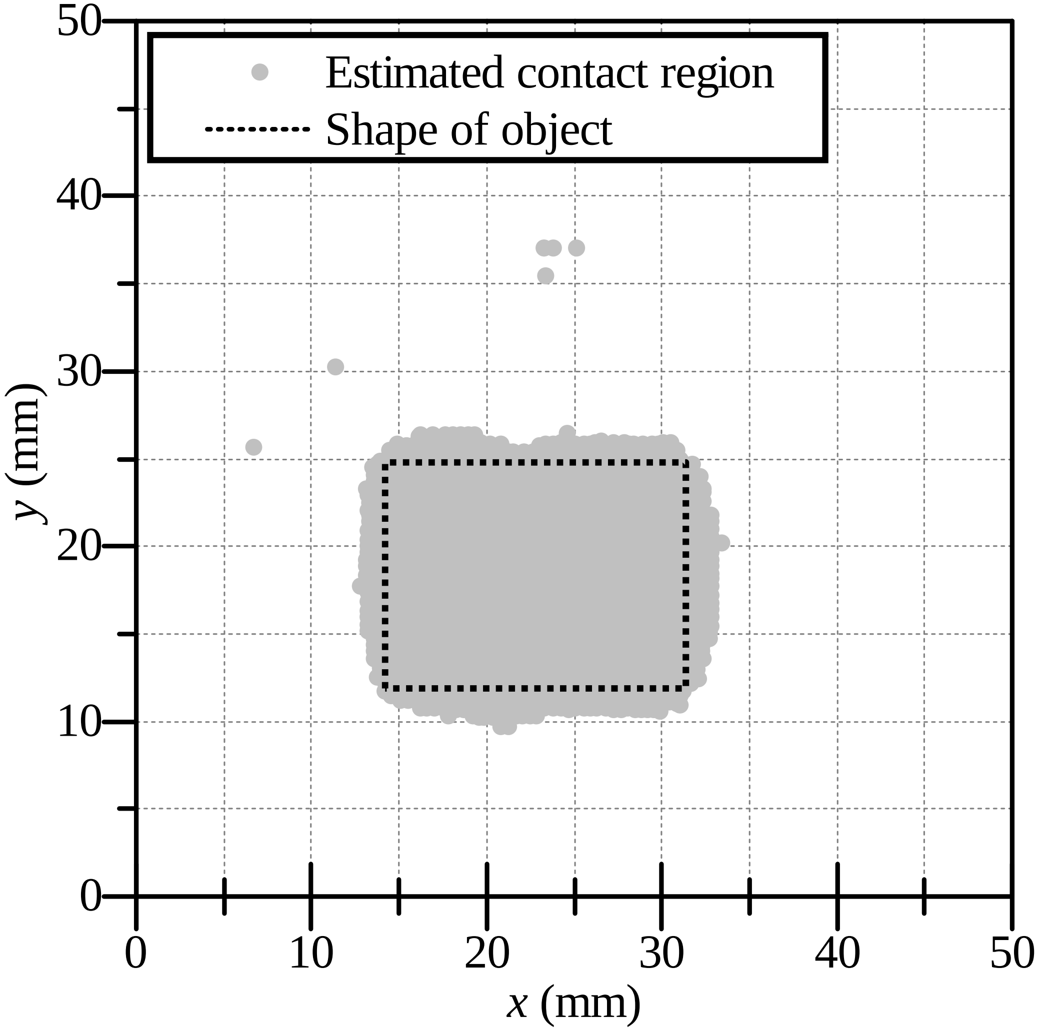
Table of Contents

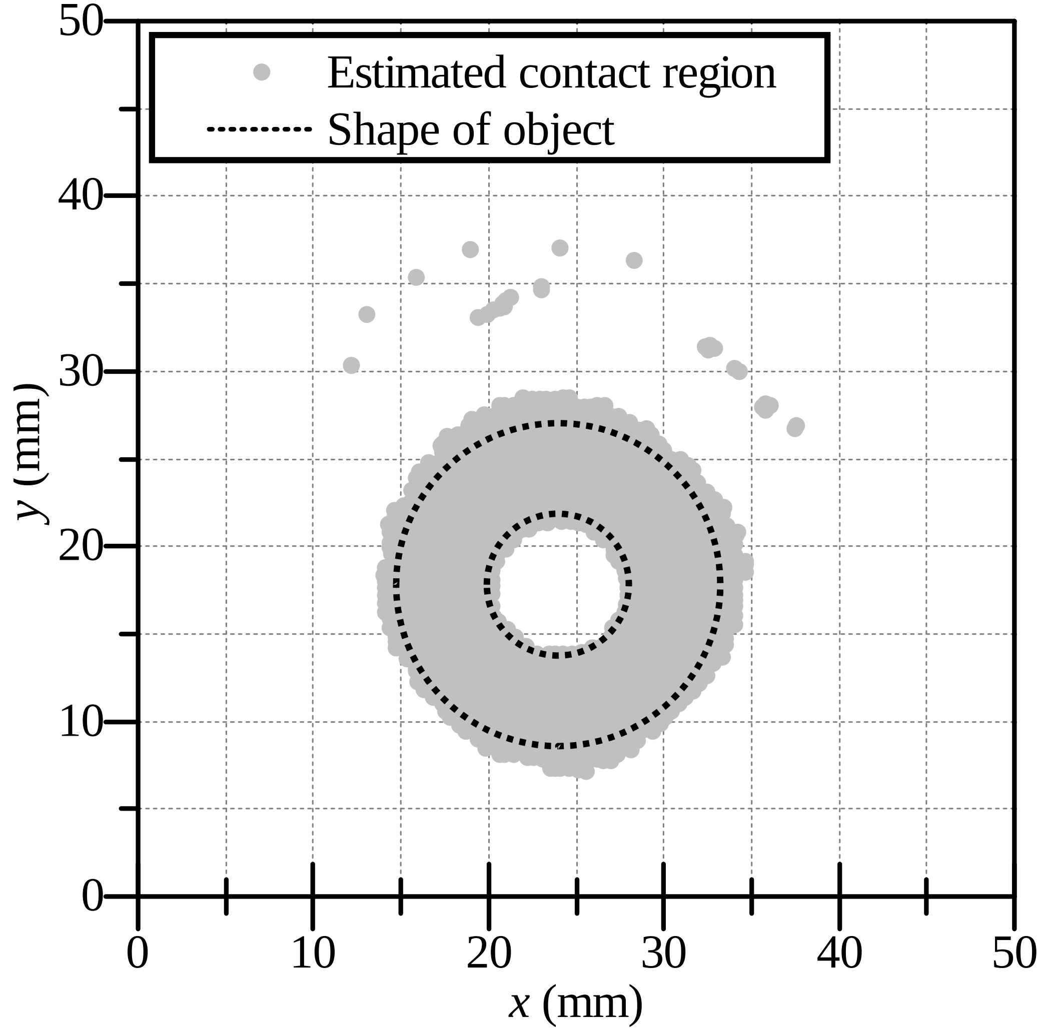
Experimental Description



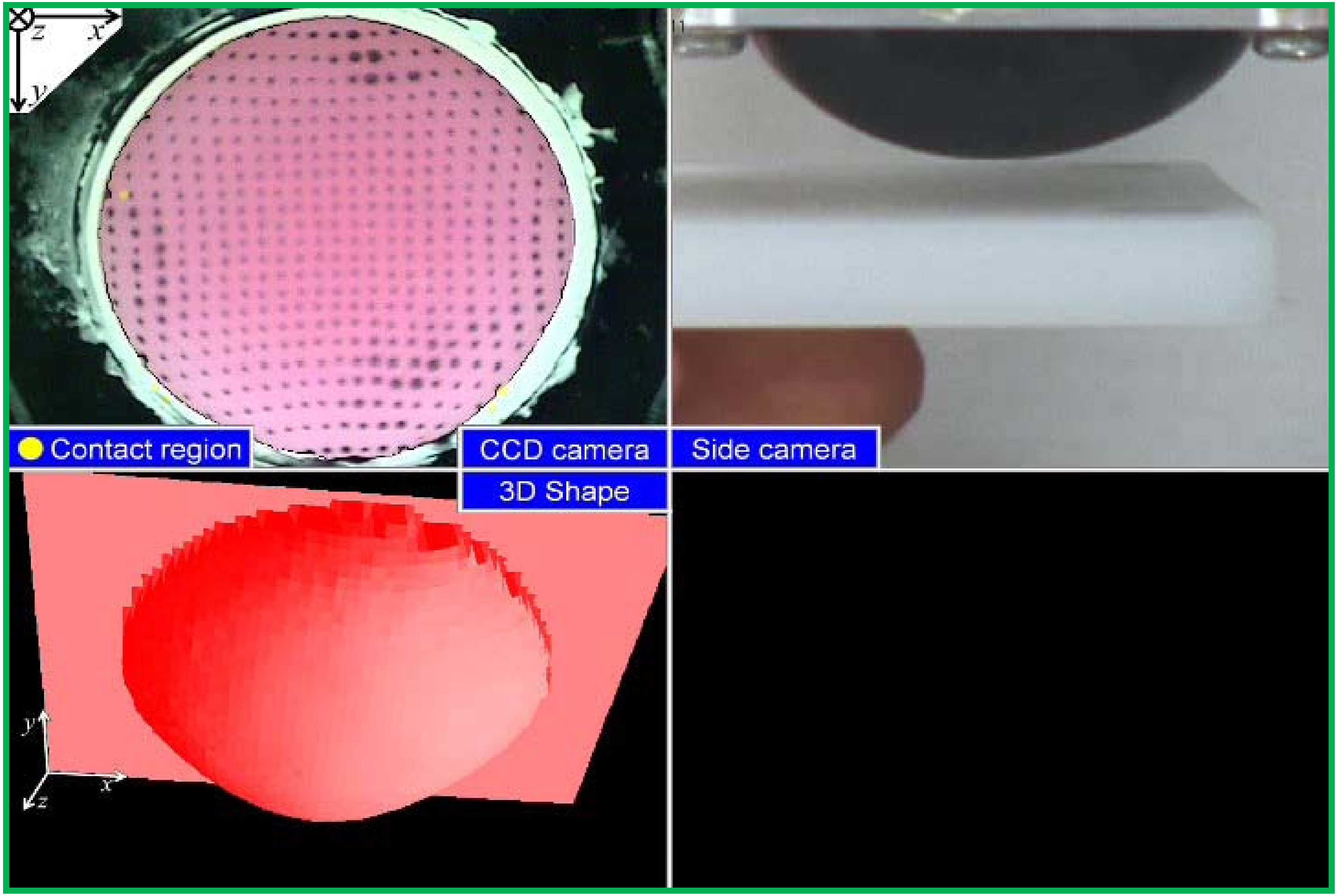
Estimation Result of Contact Region

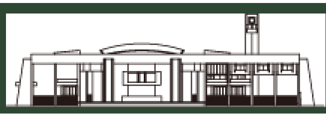
Object contacts with square/ring shaped object.



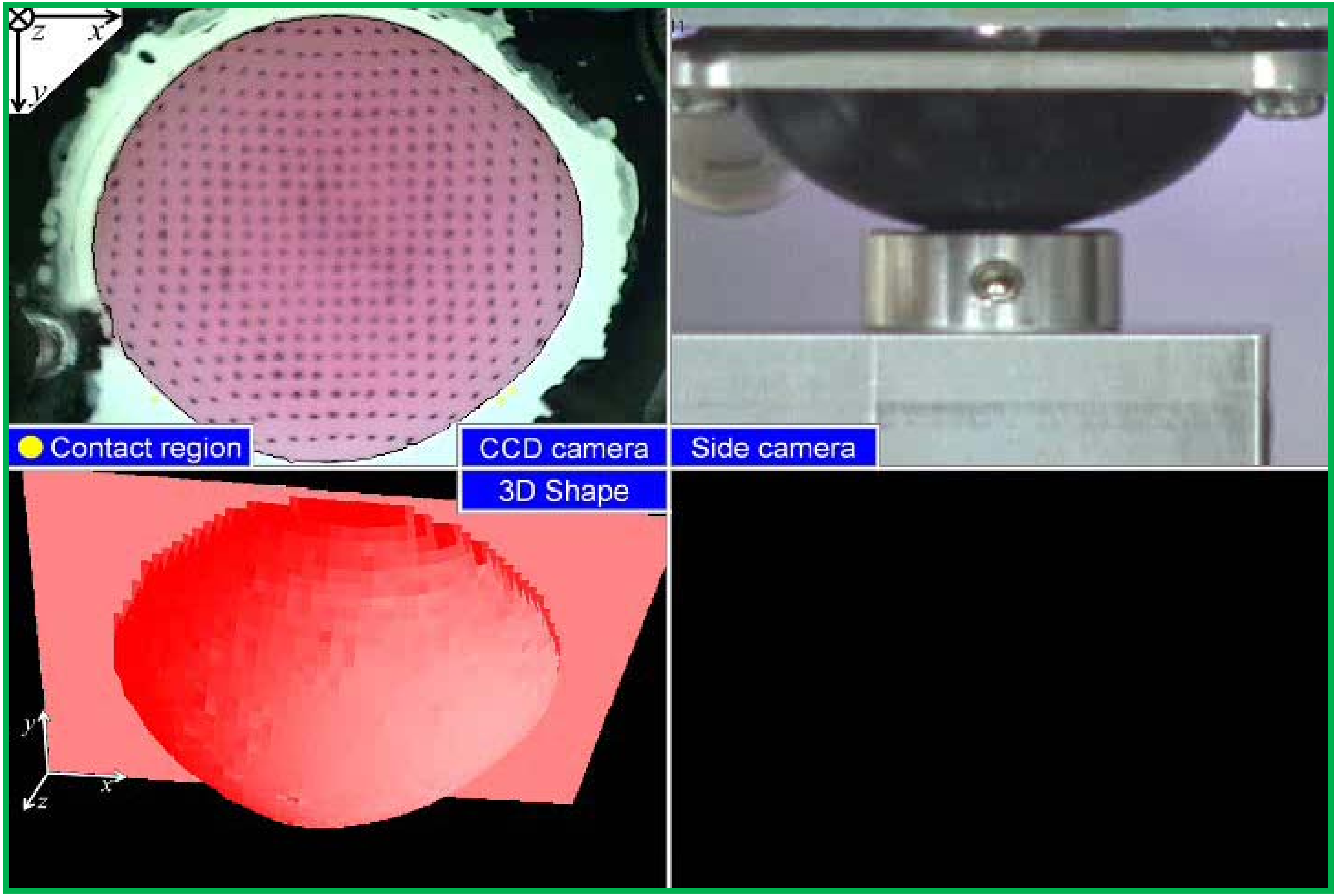


Experimental Movie of *Contact* Region Estimation



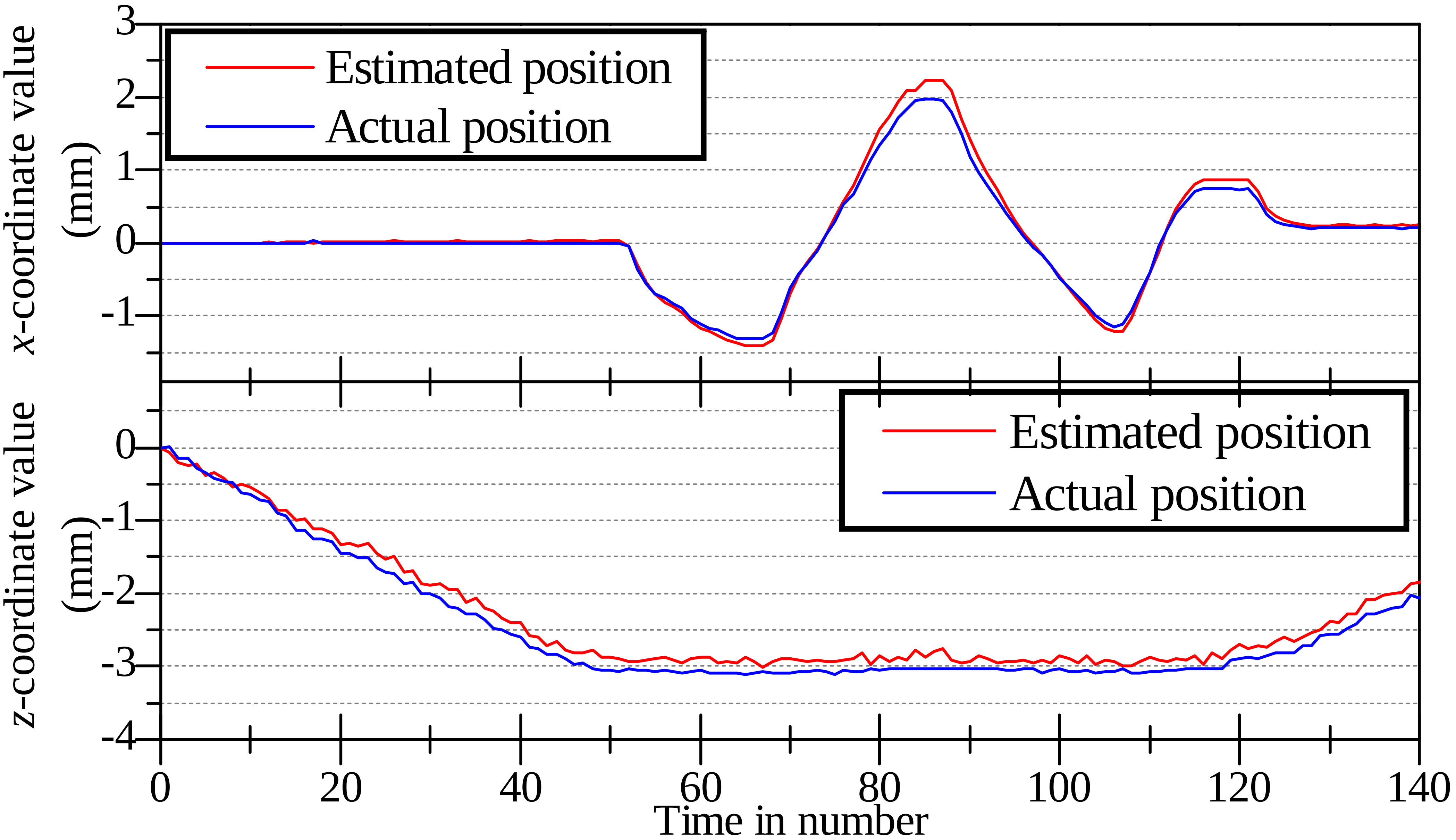


Experimental Movie of *Contact* Region Estimation



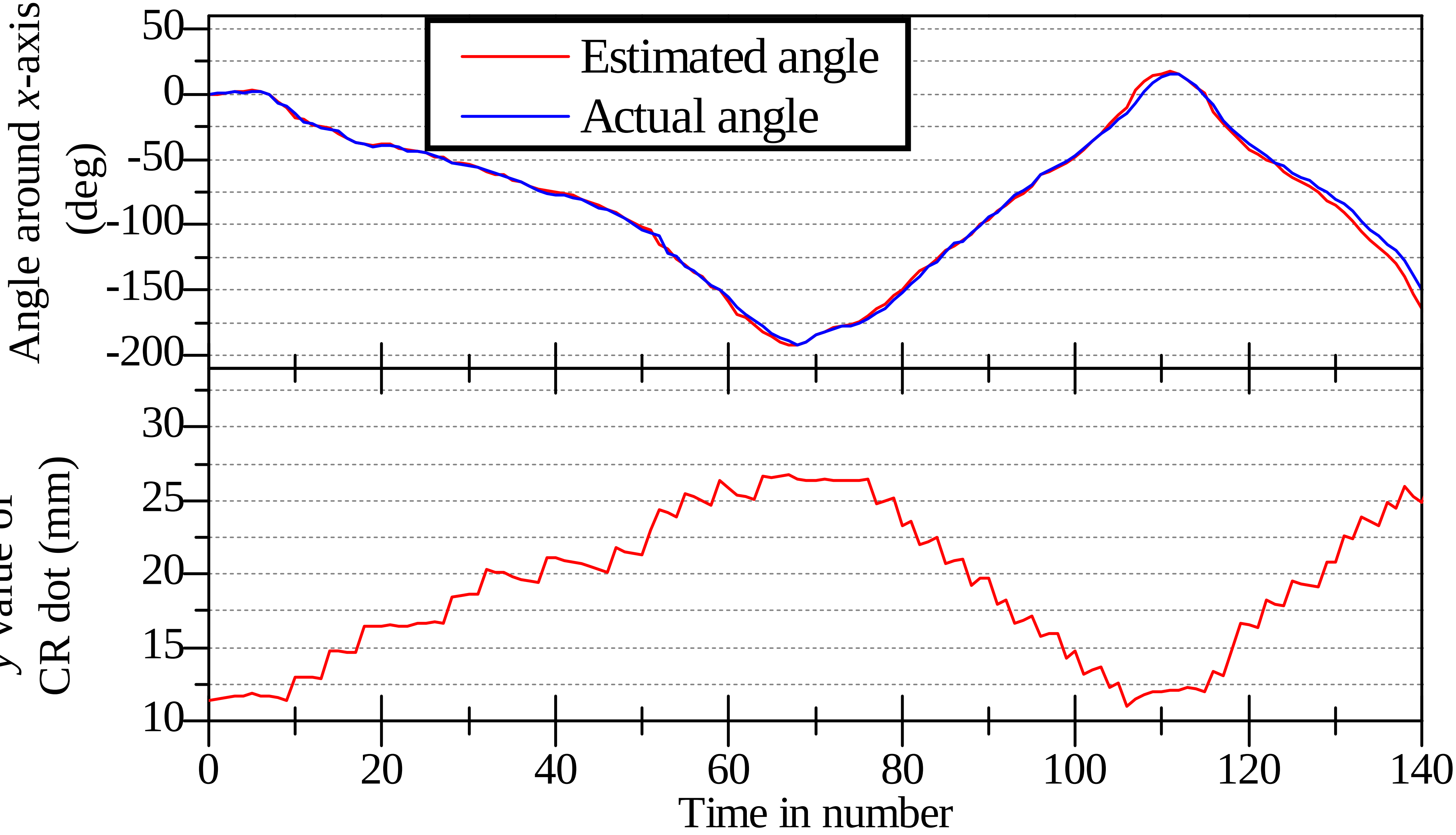
Estimation Result of Object Position

Object moves on *x-z* plane without rotation.



Estimation Result of Rotation Angle of Rolling Object

Object rolls on sensor surface.



Experimental Movie of Object Location Estimation

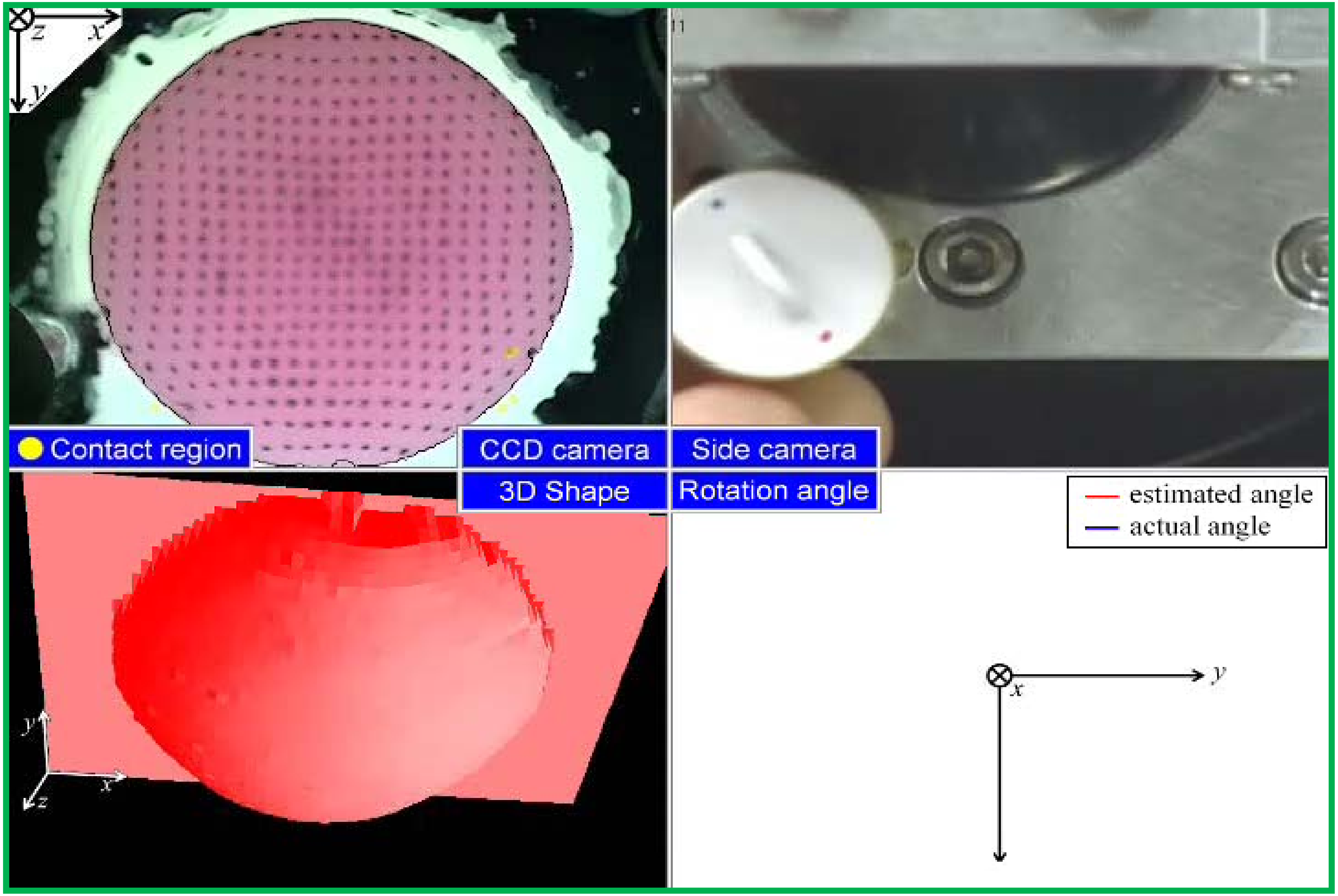


Table of Contents

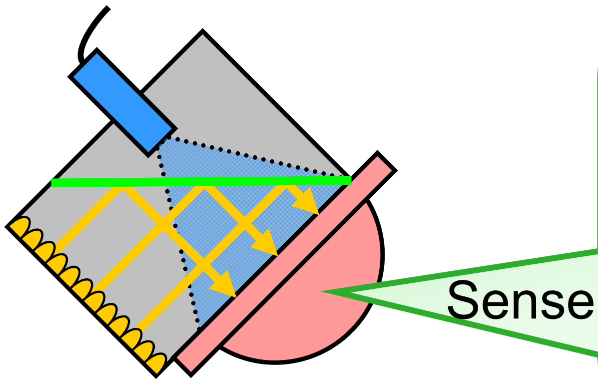
1. Introduction
2. Vision-Based Tactile Sensor
3. Contact Region Estimation
4. Object Location Estimation
5. Experimental Results
6. Conclusion

Conclusion

This paper proposed method to obtain …

- Contact region
  - ➡ to evaluate grasp stability, object shape and contact pressure
- Object location
  - ➡ to archive complex manipulation tasks

Our sensor was developed to more practical level.



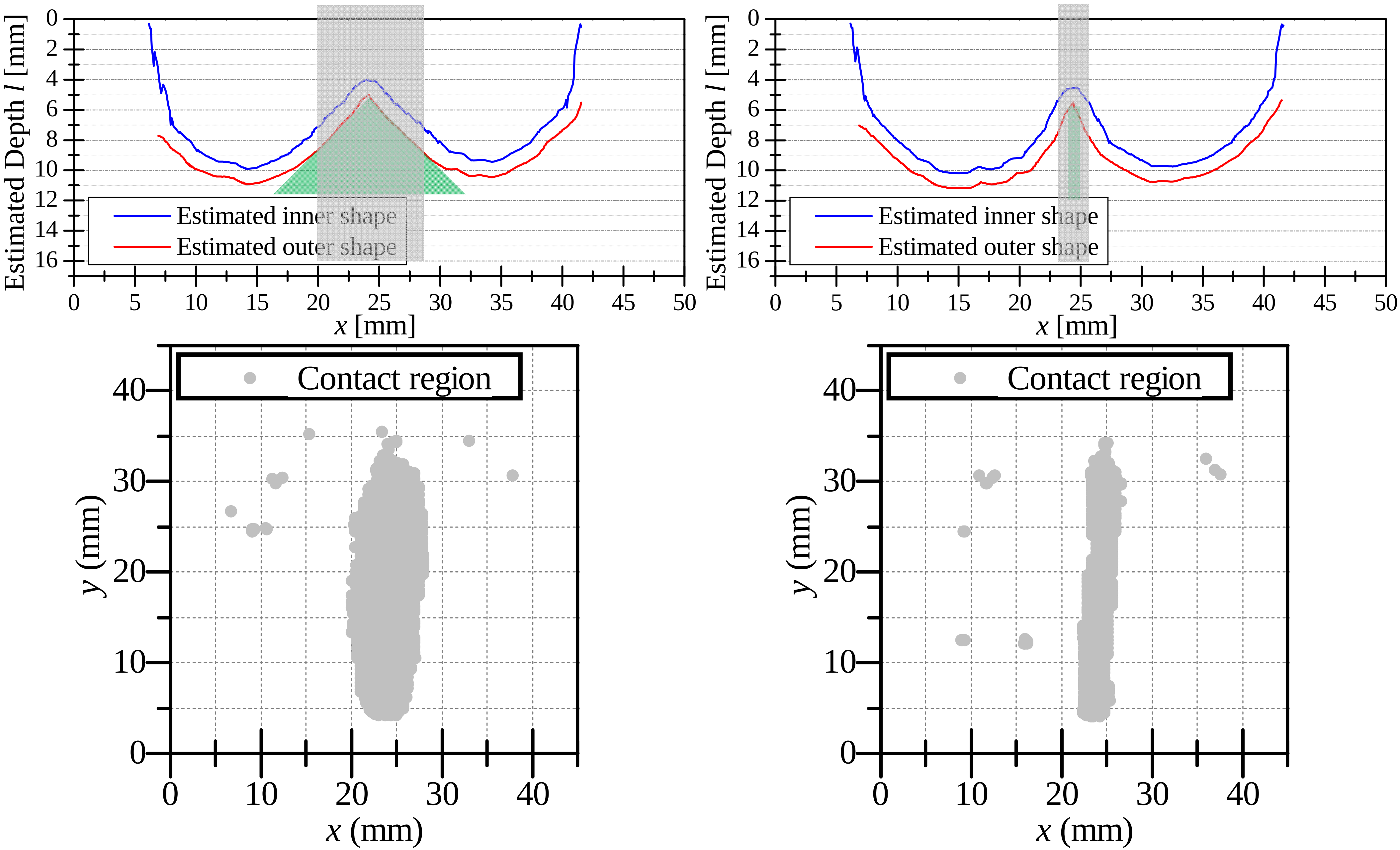
- Normal force
- Tangential force
- Moment
- Degree of slippage
- Shape/irregularity
- Contact region
- Object location

Future work

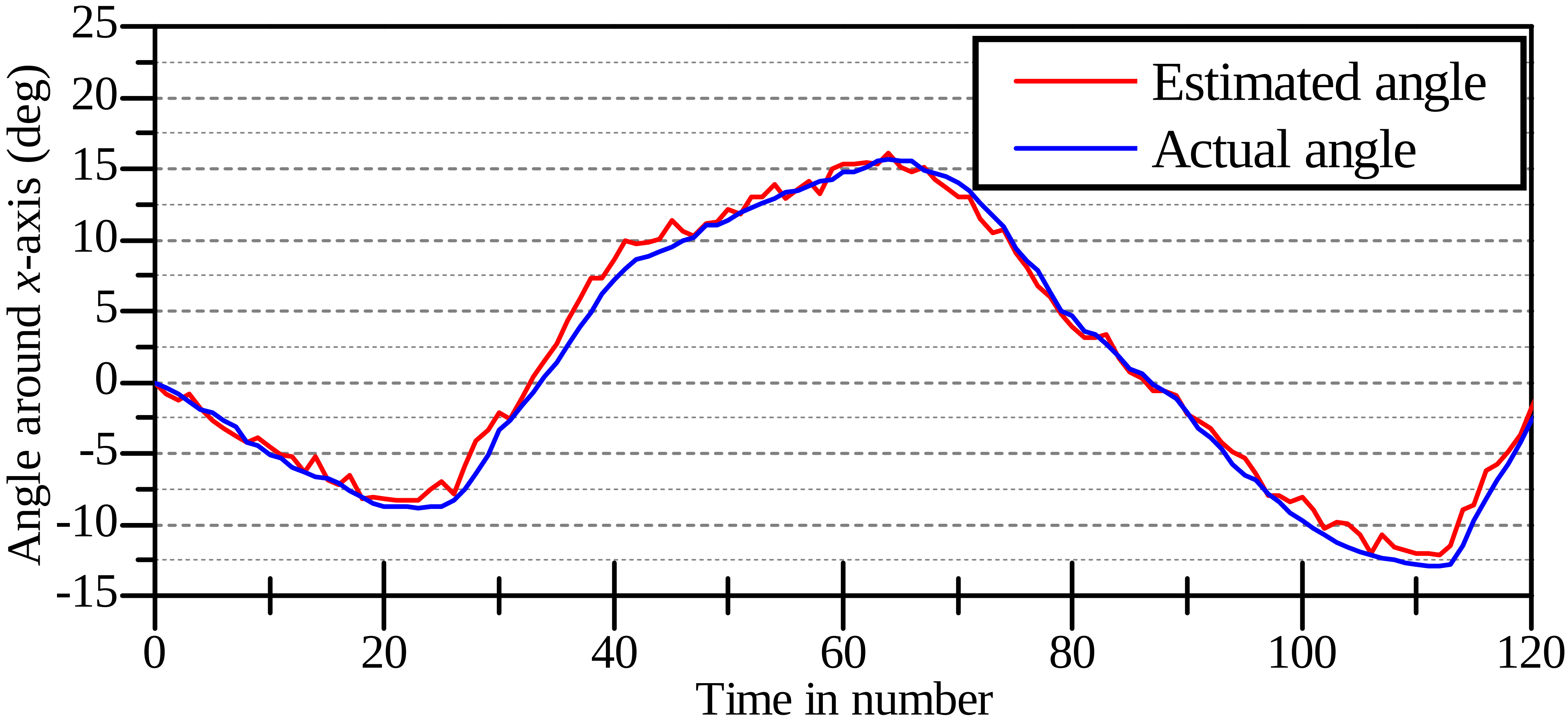
Implementation of developed sensor to robot hand to verify proposed method

Thank you for your kind attention.

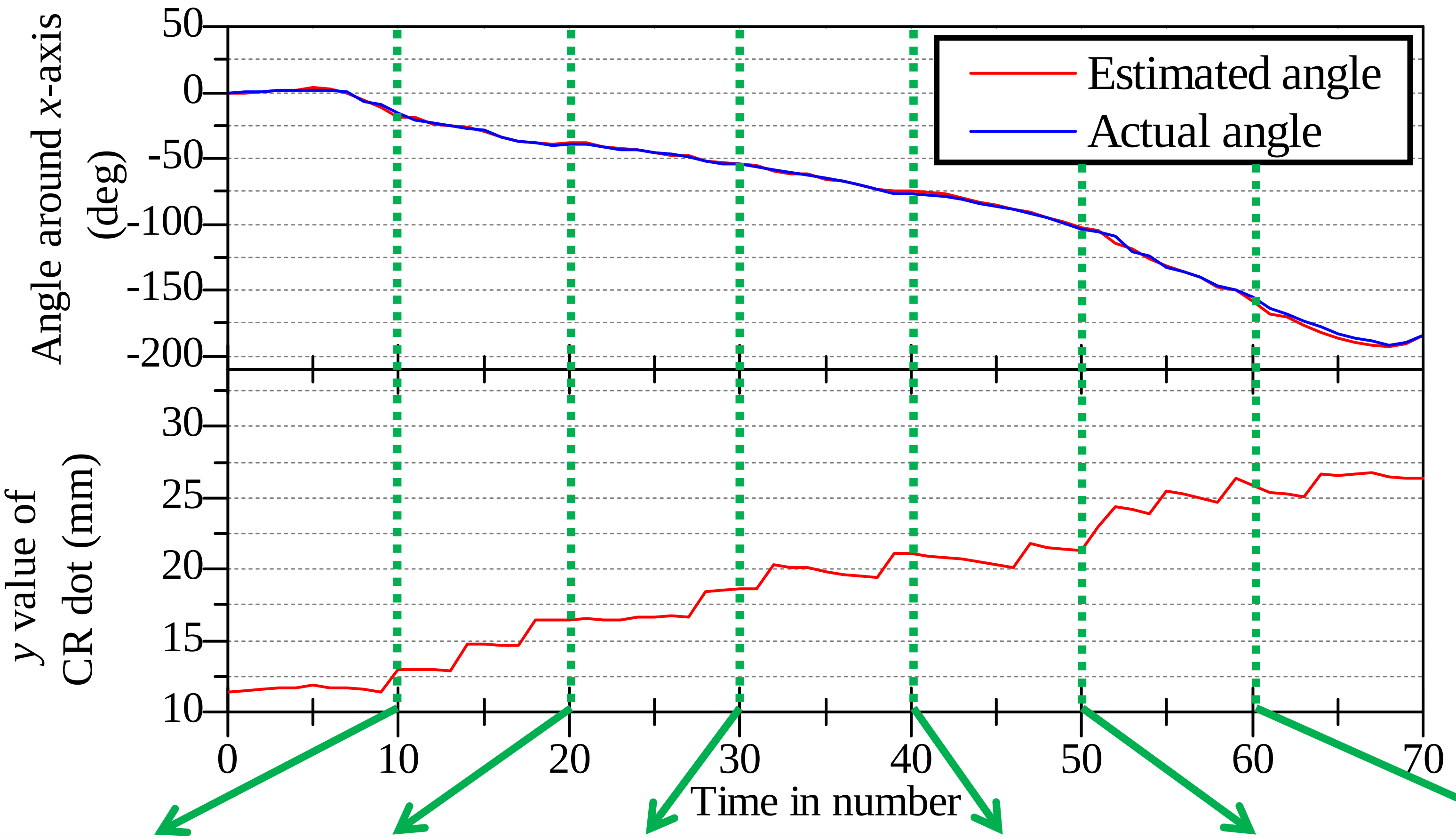
Estimation Result

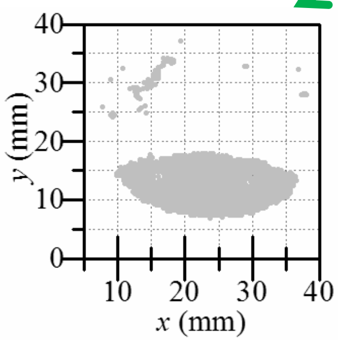


Estimation Result of Object Orientation

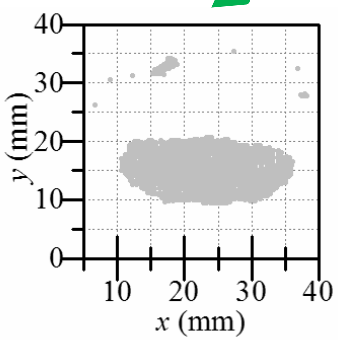


Simultaneous Acquisition

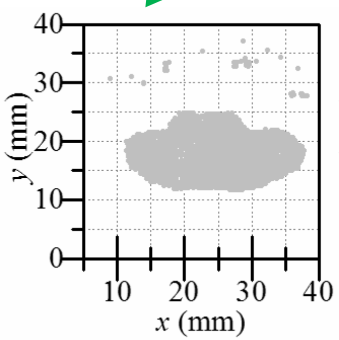




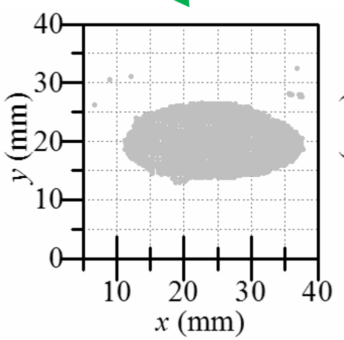
Time in number=10



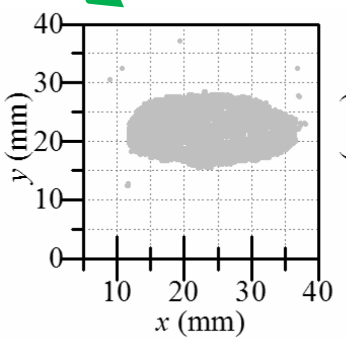
Time in number=20



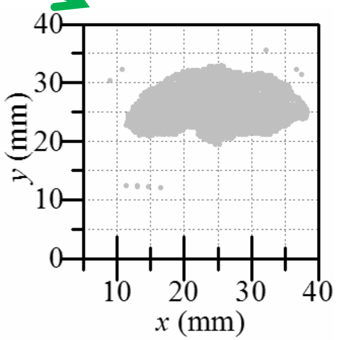
Time in number=30



Time in number=40



Time in number=50



Time in number=60

Calculation of rotation angle θ_x, θ_y, θ_z

Divide of rotation angle

$$\boldsymbol{R} = \boldsymbol{R}_z(\theta_z)\boldsymbol{R}_y(\theta_y)\boldsymbol{R}_x(\theta_x) = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix}$$

$$= \begin{bmatrix} \cos\theta_z\cos\theta_y & \cos\theta_z\sin\theta_y\sin\theta_x - \sin\theta_z\cos\theta_x & \cos\theta_z\sin\theta_y\cos\theta_x + \sin\theta_z\sin\theta_x \\ \sin\theta_z\cos\theta_y & \sin\theta_z\sin\theta_y\sin\theta_x + \cos\theta_z\cos\theta_x & \sin\theta_z\sin\theta_y\cos\theta_x - \cos\theta_z\sin\theta_x \\ -\sin\theta_y & \cos\theta_y\sin\theta_x & \cos\theta_y\cos\theta_x \end{bmatrix}$$

1. We can obtain θ_y.

2. After obtaining θ_y, we can calculate θ_x, θ_z.

Calculation for Theory of Contact Region Estimation

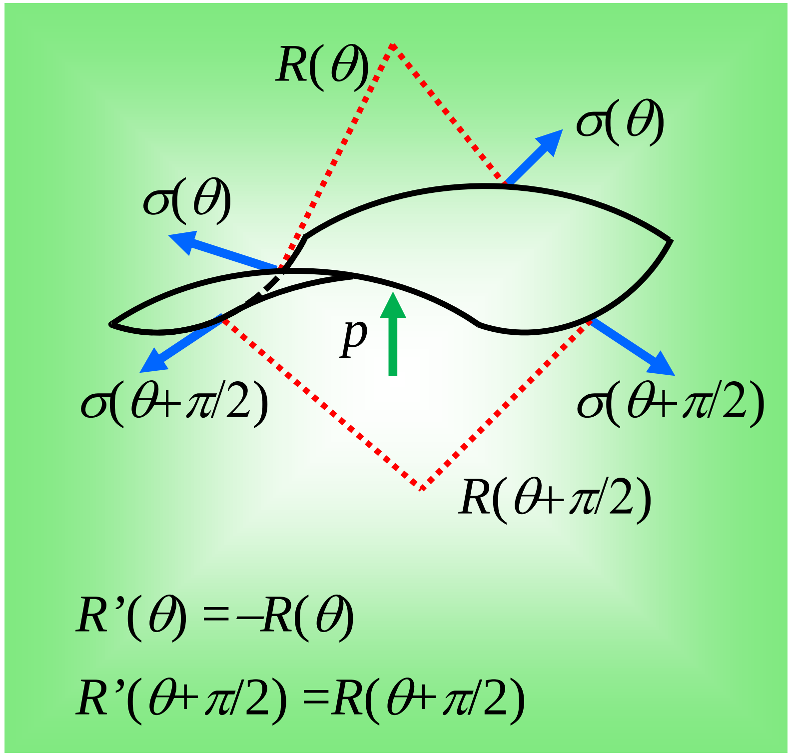
Calculation of curvature radius of each segment

We assume that the contact surface of the object is convex/flat.
Although we regard this segment as in the non contact region, it may satisfy the condition when $R'(\theta)$ is a small negative number. Therefore, when $R'(x, y, \theta)$ is negative, we set $R'(x, y, \theta)$ to $-\infty$ that yields $1/R'(x, y, \theta)=0$.

When $R'(x, y, \theta)<0$, ➡

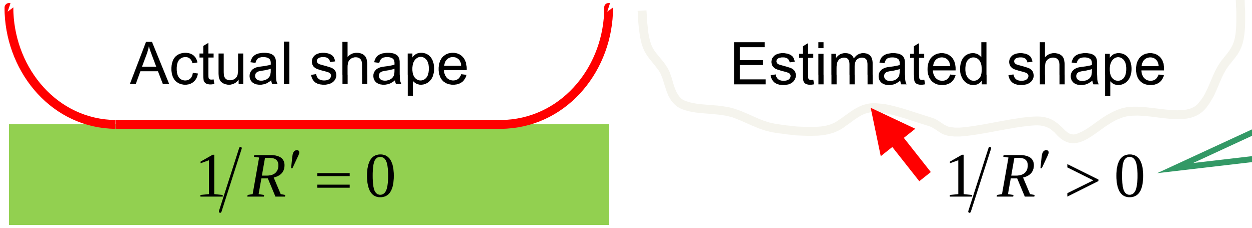
$$R'(x,y,\theta) = -\infty$$

$$\frac{1}{R'(x,y,\theta)} = 0$$



Consideration of Calculation Error

Modification of condition for P to belong to contact region



$$\frac{1}{R'(x, y, \theta)} \leq 0$$ Not satisfied

Condition for point P to be in contact region

$$\frac{1}{R'(x, y, \theta)} < \delta_R \qquad (0 \leq \theta < \pi \, [\mathrm{rad}])$$

$$\delta_R = \min\{E_R(x, y, \theta) - 2\sigma_R(x, y, \theta)\}$$

E_R : average values of $1/R'$

σ_R : standard deviation of $1/R'$

when touch pad doesn't contact

Smaller σ are desirable.

$$f(x, y) \equiv \frac{1}{n} \sum_{i=1}^{n} \frac{1}{R'\left(x, y, \pi \frac{i}{n}\right)} < \delta_f$$

$$\delta_f = \min\{E_f(x, y) - 2\sigma_f(x, y)\}$$

E_f : average values of f

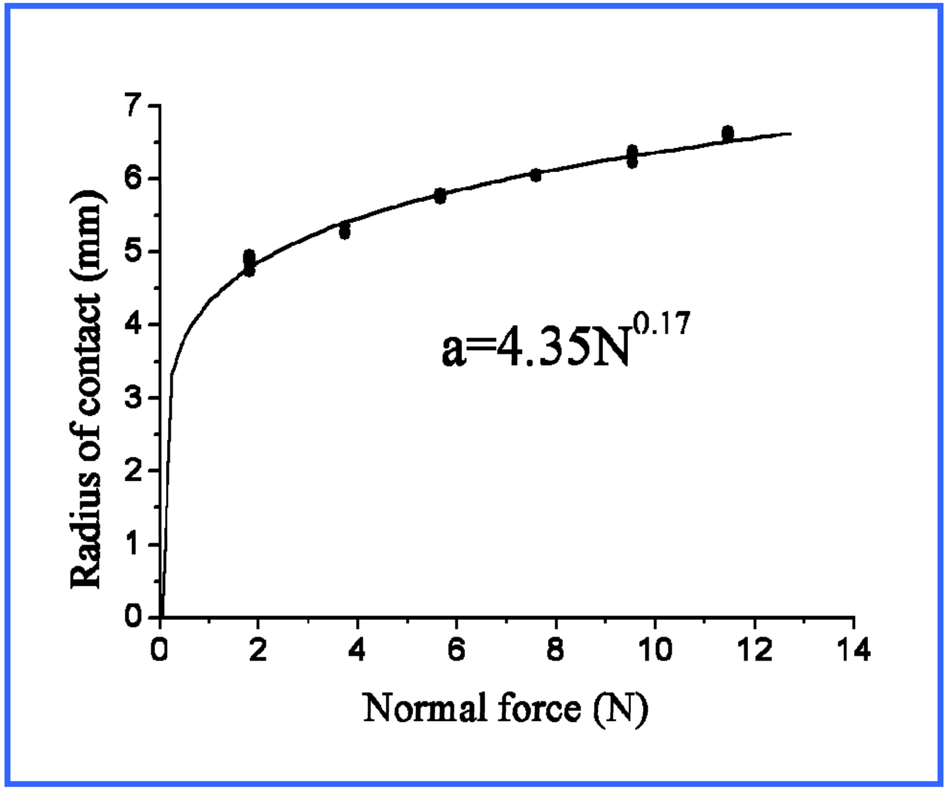
σ_f : standard deviation of f

when touch pad doesn't contact

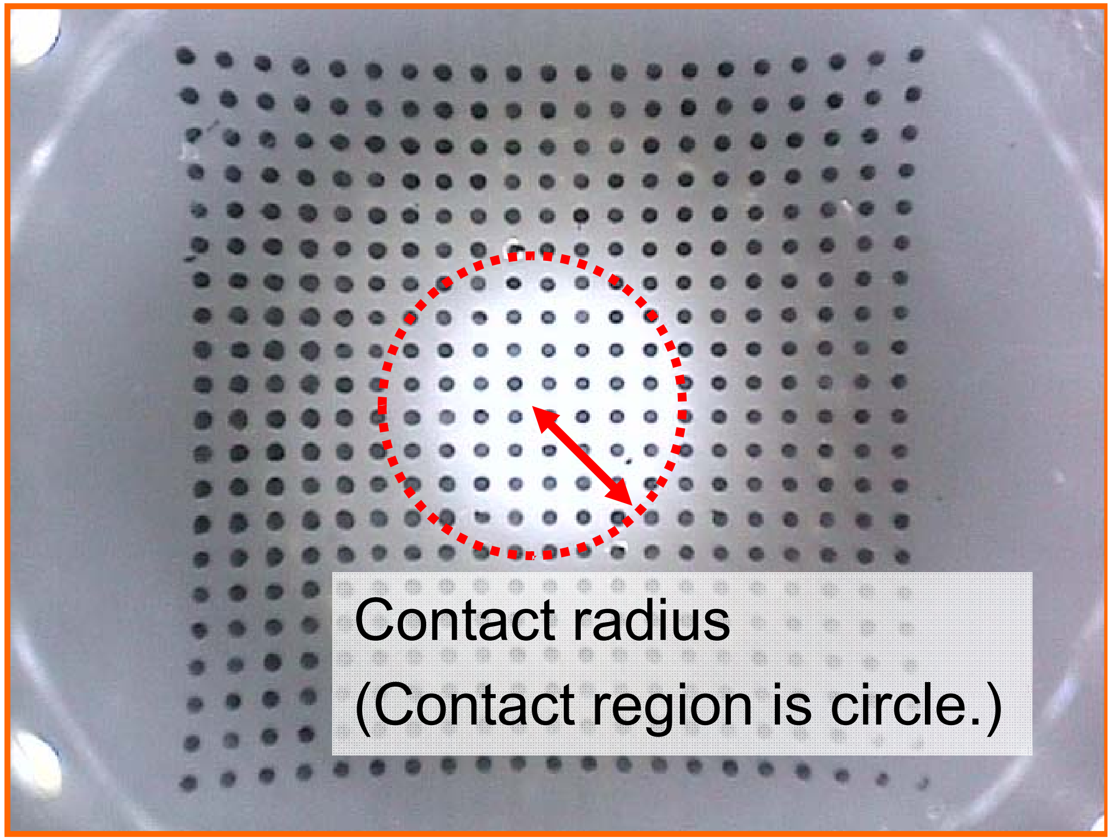
$\sigma_f < \sigma_R$ $\quad$ σ is decreased.

Measurement of Contact Force

- Normal force
- Tangential force
- Moment



Relation between normal force and contact radius

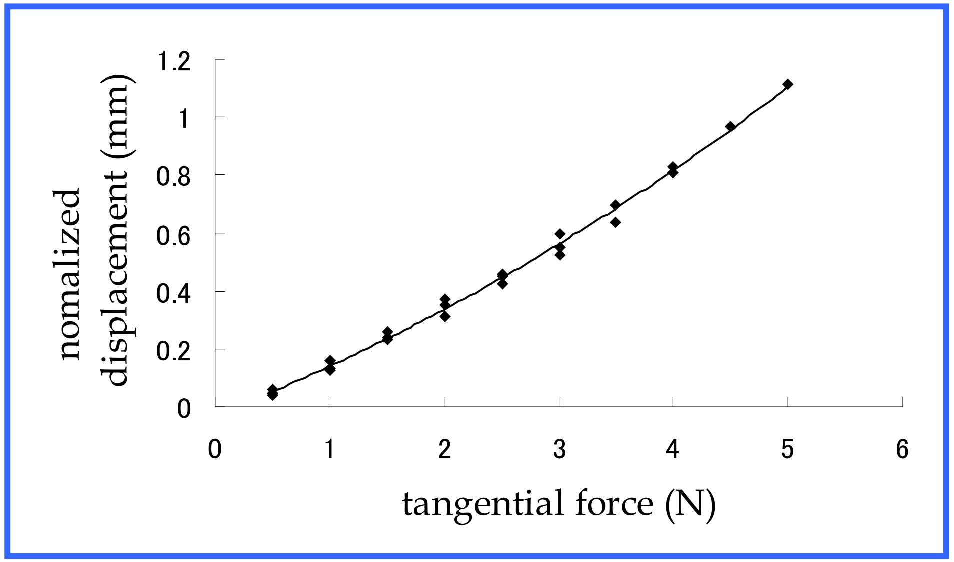


Refrence

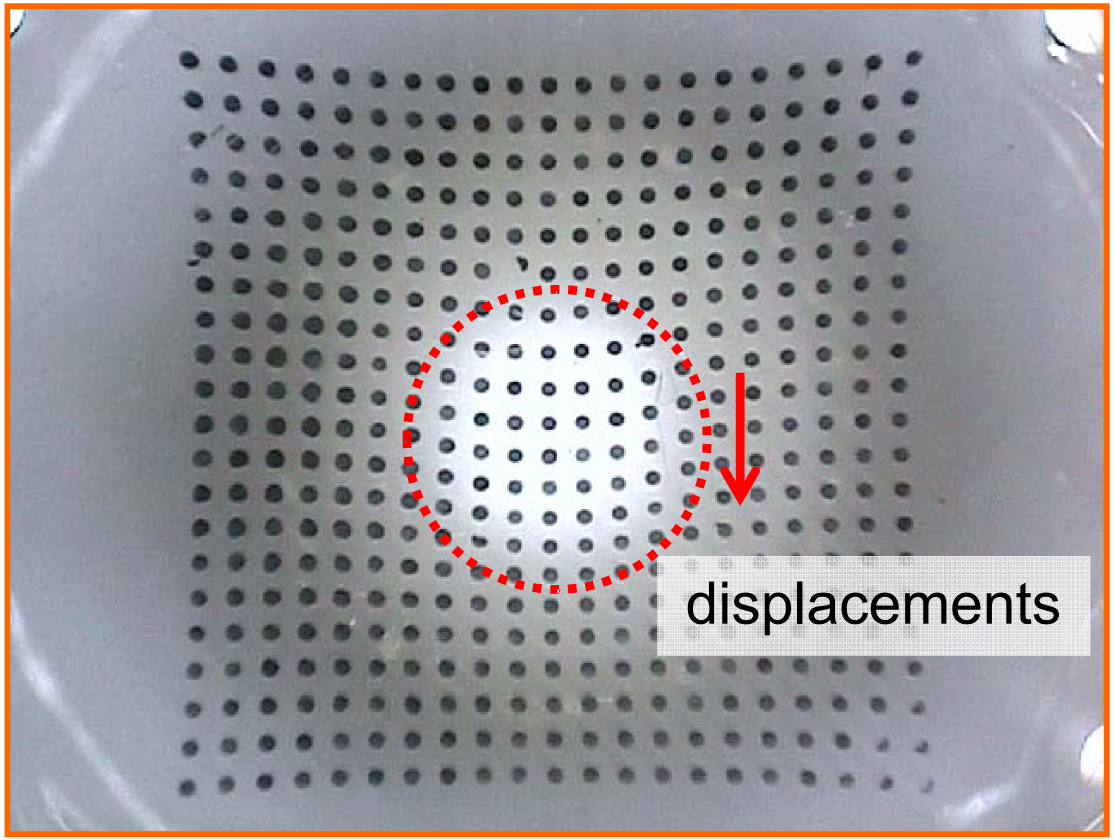
Xydas, Kao：Modeling of contact mechanics and friction limit surface for soft fingers in robotics with experimental results, International Journal of Robotics Research, Vol.18, No. 8, pp.941-950 (1999).

Measurement of Contact Force

- Normal force
- Tangential force
- Moment

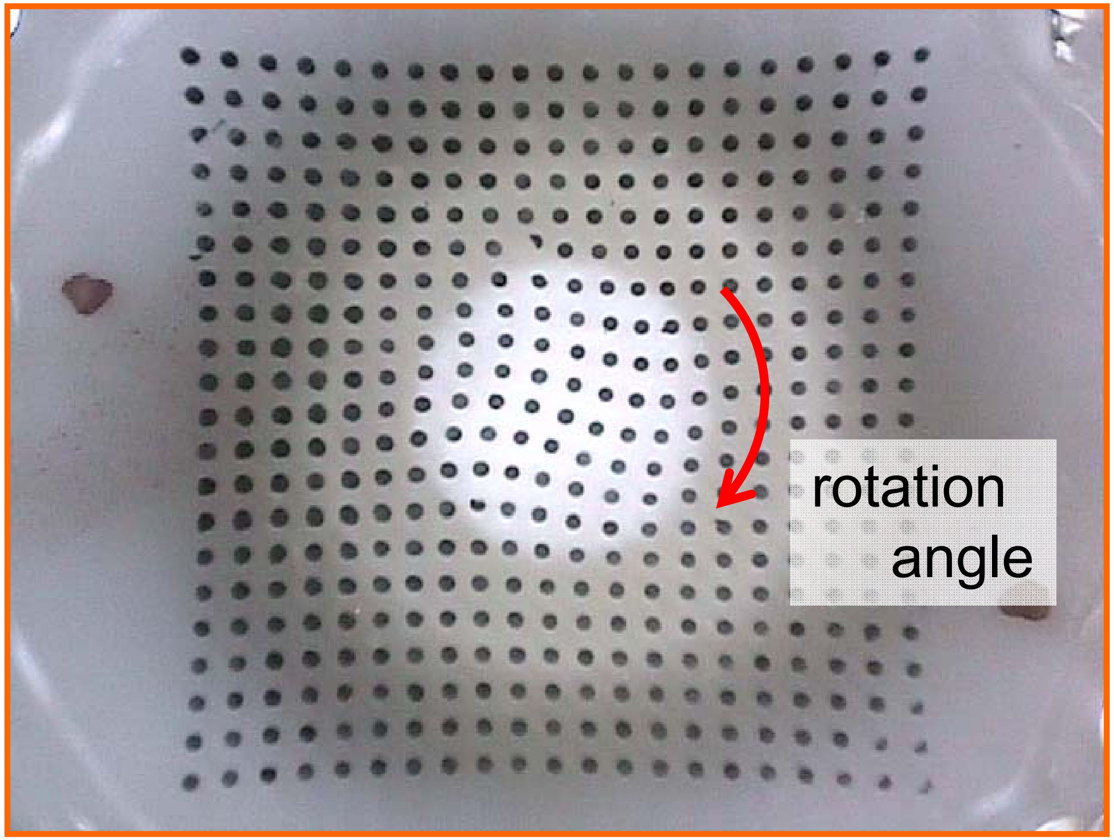


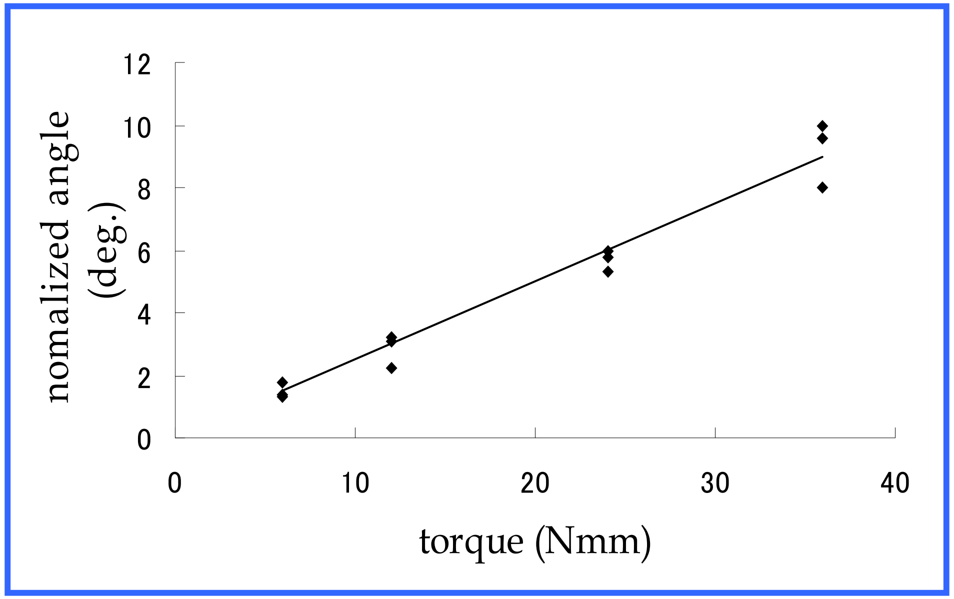
Relation between tangential force and displacements of dots



Measurement of Contact Force

- Normal force
- Tangential force
- Moment

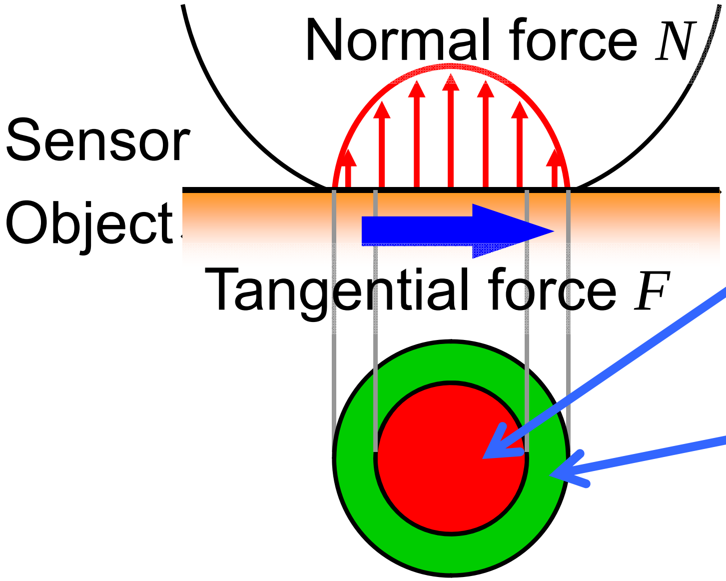




Relation between moment
and rotation angle of contact surface

Estimation of Slippage Degree

Partial slippage by non linear pressure distribution



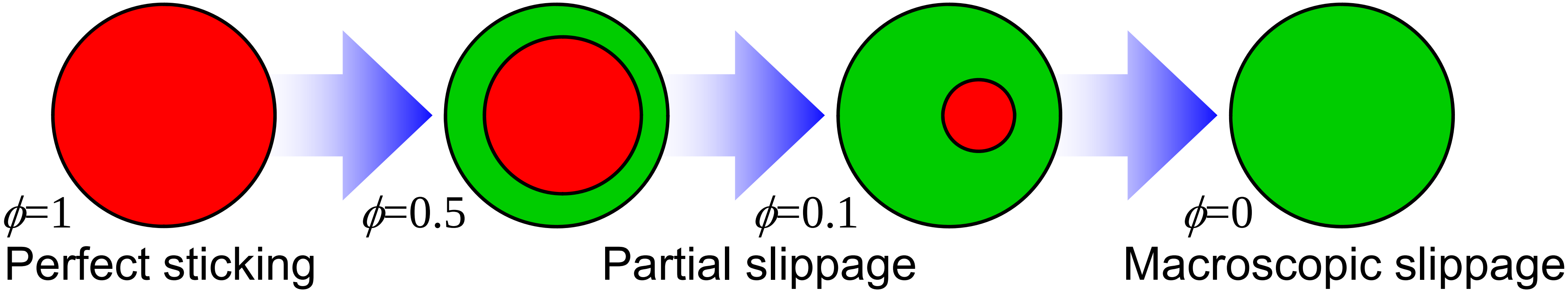
Contact region S_c

Stick region S_s
$F < \mu N$

Incipient slippage region $F > \mu N$

Stick ratio $\phi = \dfrac{S_s}{S_c}$

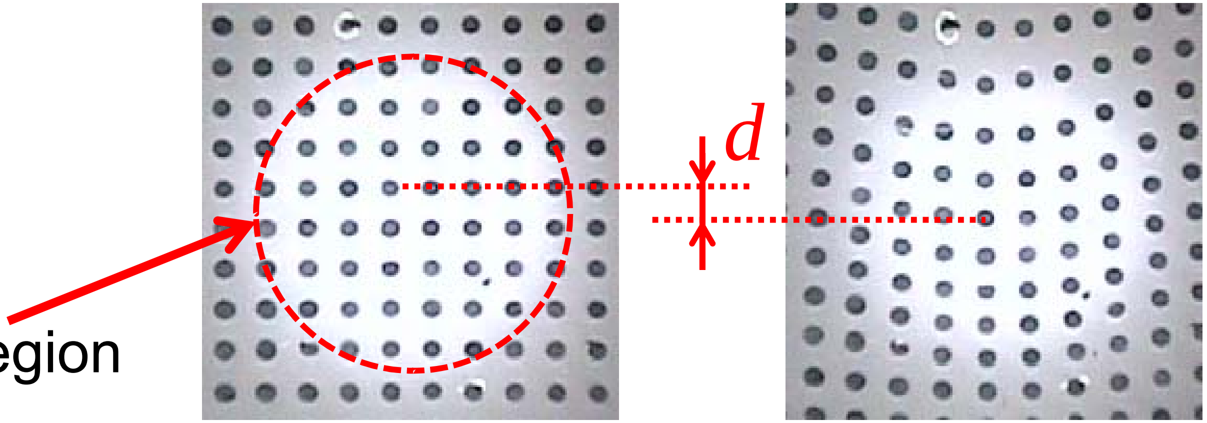
Stick ratio indicates slippage degree.



Keeping $\phi > 0$ → Preventing object from slipping

Stick Ratio Estimation Method

Discrimination of stick/slippage region



Contact region

Initial image

Current image

Displacement

d_k : Each dot

d_0 : Central dot ≒ Object

$|d_0 - d_k| < \delta$ In stick region

$|d_0 - d_k| > \delta$ In slippage region

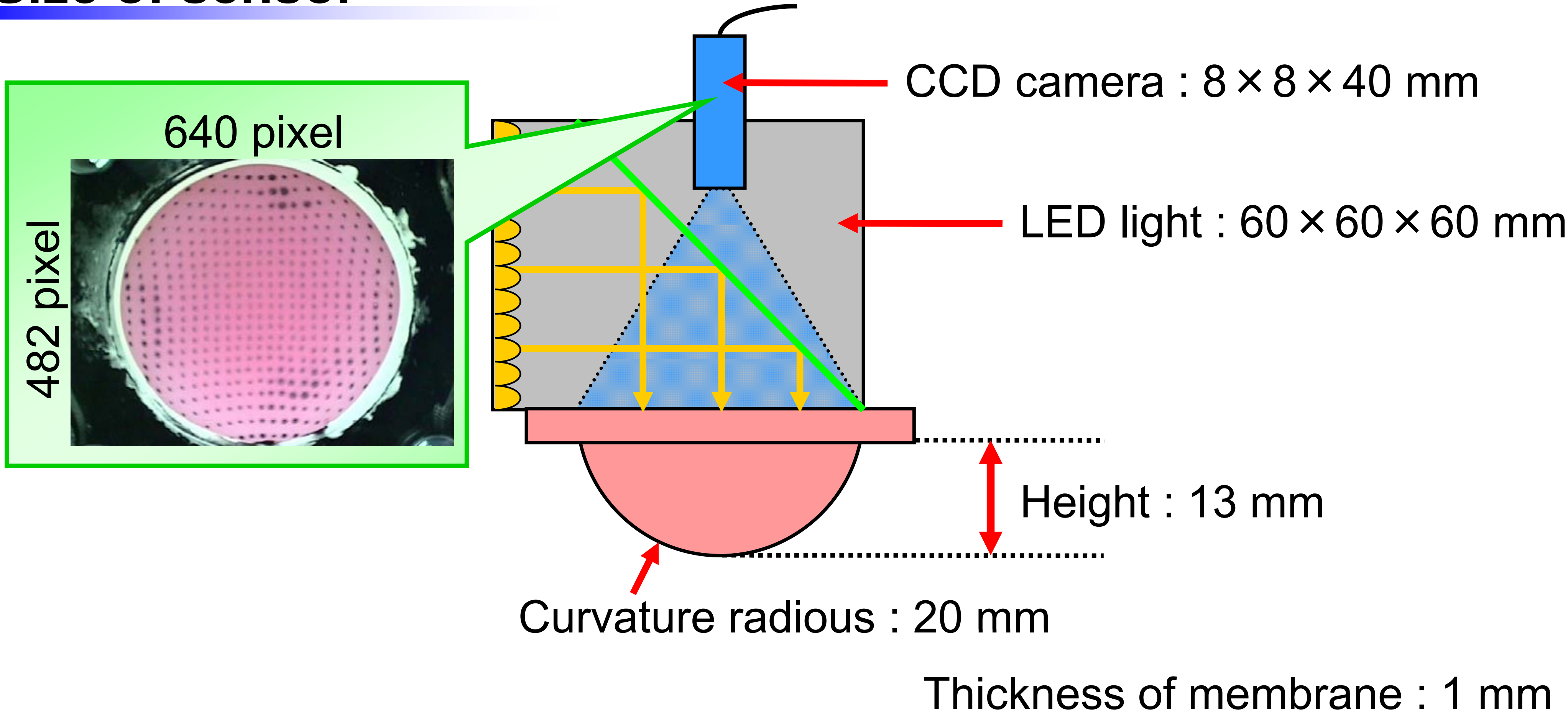
Stick ratio $\phi = \dfrac{S_s}{S_c} \cong \dfrac{N_s}{N_c}$

N_s : Number of dots in stick region

N_c : Number of dots in contact region

Forecasted Question

Size of sensor



Processing speed

Although the processing speed is about 2Hz currently, we can process the method faster by using high spec PC and parallel computing method such as CUDA .

Forecasted Question

- 回転と平行移動が重なったらどうなるの？When the movement and rotation occur simultaneously, it is hard to define the position of the object. For example, when we define the object position as the position of the weighted center of the object, we cannot estimate the displacement with the rotation.
- なぜシリコーンゴム？The silicon rubber is hardly influenced by the environment.
- Vision-based 以外のセンサってどんなのがあるの？electrical resistance, capacitance, electromagnetic component, piezoelectric/ ultrasonic/ component, strain gauge.
- 接触領域分解能は？We estimate the contact region, changing the center point P of the segment by 5pixel (0.4mm). It is the resolution. When we estimate changing P by smaller distance, the resolution is increased.
- 物体位置分解能は？The resolution of the object location depends on the shape estimation of the touch pad. the resolution of the estimated shape is about 1 μm but mean error is 0.5 mm. Therefore, the resolution of the object position is 1 μm but maximum error is about 0.5 mm.
- 物体角度分解能は？The resolution of the rotation angle is about 0.04 deg which is calculated from the resolution of the pad shape and the equation to acquire the angle. (Distance between 2 dots is 1.5 mm and resolution of shape is 1 μm.) But maximum error is about 10 deg. This is due to the error of the shape estimation.

Forecasted Question

- 一般性は？スケーラブル？The shape and size of the touch pad is arbitrary. However, the sensor requires the resolution of the CCD camera to detect the position of dots. Therefore, when we change the CCD camera, we have to change the number of dots. And when we estimate the force and slippage, the elastic body must have the convex surface.
- rはどうやって決める？*r* is determined as 1.92 mm（25pixel）which was obtained experimentally. The size of *r* has trade-off between the variation of the calculated curvature radius and the estimation accuracy for a sharp curve.