Robust micro/nano-positioning by visual servoing

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January 26th, 2016
Micro/nano-technology

- Material Science
- Mechanical Eng.
- Physics
- Life Science
- Chemistry
- Biology
- Information Technology
- Electrical Engineering
- Computer Science

- Flexible circuit
- Nanomedicine

- 1 nm glucose molecule
- 10 nm DNA
- 1 μm bacteria
- 10 μm red cell
- 100 μm human hair
- 1 mm ant

- Nylon nanofibers

Cornell Univ.

Univ. of Pennsylvania
Project context

• ANR (French National Research Agency) **Nanorobust** project
• Fundamental aspects in micro/nano-materials characterization and positioning in Scanning electron microscopes (SEM)
• Collaboration of 4 French laboratories
  - FEMTO-ST
  - IRISA
  - ISIR-UPMC
  - LPN-CNRS
Robotics in micro/nano-scale

• Automated micro/nano-manipulation and assembly
  • to characterize the properties of nanostructures
  • for nanomaterial manufacturing

• Visual information is one of the most important way to observe the micro/nano-object
• Motivation: achieve robust micro/nano-positioning tasks using visual servoing techniques

One-by-one positioning of seven nanodiamonds using a nanomanipulation stage in a SEM (MIT, US)

A microfabricated electrostatic gripper inside a SEM to pick up silicon nanowires (DTU, Denmark)
Vision-based control in micro/nano-scale

- Visual servoing: control the robot motion based on visual information [Hutchinson,96] [Chaumette,06]

- Vision-based control in micro/nano-scale
  - Handling guidance [Koyano,96] [Vikramaditya,97]
  - Fusion of force sensing and visual feedback [Zhou,98]
  - Multiview system [Sun,04][Probst,09]
  - 2 DoFs [Marturi,14], 3 DoFs [Sievers,05] [Ru,11] [Tamadazte,12] [Gong,14], 6 DoFs (by CAD model-based tracking) [Kratochvil,09] [Tamadazte,10]
Challenges

• Vision instrument: *microscope*
• *Scanning electron microscope (SEM)*
• Image formation process & geometric projection models: different from the optical camera
• Robotic platform
• Installed inside the SEM vacuum chamber
• Small step resolution (increment) and high accuracy
Scanning Electron Microscope

- Generating images by scanning the surface of the sample using electron beam
- Magnification: 10x to 500,000x
SEM image issues

• Image quality vs. scan speed: find a good compromise

Medium scan speed

Fast scan speed

images acquired by Zeiss EVO LS 25 SEM (ISIR)
SEM image issues

- Image quality vs. scan speed: find a good compromise
- Image drift: almost insignificant in a short time

Images acquired by Zeiss EVO LS 25 SEM (ISIR)
**Content**

- **SEM Calibration**
- **SEM autofocus**
- **Robot motion control along depth direction**
- **SEM focus control**
- **6-DoF micro/nano-positioning**
- **Visual tracking**

*parallel projection: Difficult to observe the motion on Z axis*
Outline

- SEM calibration
- Controlling the motion along the depth direction
- Micro and nano-positioning by visual servoing
- SEM autofocusing
- Visual tracking and pose estimation
SEM calibration

• To determine the relation between the 3D coordinates of a point on the observed sample and its projection on the image plane

• Challenges with a SEM
  • Geometric projection models selection [Sinram,02] [Cornille,03]
  • Spatial distortions [Schreier,04] [Malti,12]
SEM projection models and distortions

Geometric projection models [Sinram,02] [Cornille,03]
SEM projection models and distortions

Geometric projection models [Sinram,02] [Cornille,03]

- **Perspective projection**
  - at low magnifications
SEM projection models and distortions

Geometric projection models [Sinram,02] [Cornille,03]

- **Perspective projection**
  - at low magnifications
- **Parallel projection**
  - at high magnifications
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  - at low magnifications

• **Parallel projection**
  - at high magnifications
SEM projection models and distortions

Geometric projection models [Sinram,02] [Cornille,03]

- **Perspective projection**
  - at low magnifications
- **Parallel projection**
  - at high magnifications

Image spatial distortions

  a) Radial distortion
  b) Skewness
  c) Spiral distortion
SEM calibration parameters

Parameters to be estimated in calibration:

- **Intrinsic parameters**: SEM property provided by manufacturers
  \[ p_x, p_y : \text{pixel/meter ratio} \]
  \[ u_0, v_0 : \text{coordinates of the principle point} \]
- **Extrinsic parameters**: microscope pose in the world coordinates
  \[ \mathbf{r} = (X, Y, Z, \theta_X, \theta_Y, \theta_Z) \]

- **Perspective projection**
  \[
  \begin{bmatrix}
  u \\
  v \\
  1
  \end{bmatrix} = \begin{bmatrix}
  p_x & 0 & u_0 \\
  0 & p_y & v_0 \\
  0 & 0 & 1
  \end{bmatrix} \begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & 0
  \end{bmatrix} \begin{bmatrix}
  cX \\
  cY \\
  cZ \\
  1
  \end{bmatrix}
  \]

- **Parallel projection**
  \[
  \begin{bmatrix}
  u \\
  v \\
  1
  \end{bmatrix} = \begin{bmatrix}
  p_x & 0 & 0 \\
  0 & p_y & 0 \\
  0 & 0 & 1
  \end{bmatrix} \begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & 0
  \end{bmatrix} \begin{bmatrix}
  cX \\
  cY \\
  cZ \\
  1
  \end{bmatrix}
  \]
SEM calibration parameters

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  cZ \\
  1
  \end{bmatrix}
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  0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 1
  \end{bmatrix} \begin{bmatrix}
  cX \\
  cY \\
  cZ \\
  1
  \end{bmatrix}
  \]
Non-linear calibration process

- Minimize the residual error by modifying the intrinsic parameters and the extrinsic parameters simultaneously.

- Cost function \( \hat{r}, \hat{\xi} = \arg\min_{r, \xi} \sum_{i=1}^{N} (i\mathbf{x}_p(r,\xi) - i\mathbf{x}_p^*)^2 \)

- Initial estimation computed by a linear algorithm [Zhang, 00]

- Update the pose \( \mathbf{r} \) and the intrinsic parameters \( \xi \) iteratively \( \mathbf{v} = \begin{bmatrix} \dot{r} \\ \dot{\xi} \end{bmatrix} \)

\[ \mathbf{V} = -\lambda \mathbf{J}_p^+(\mathbf{x}_p(r, \xi) - \mathbf{x}_p^*) \]

- Temporal variation of pixel positions

\[ \dot{\mathbf{x}}_p = \frac{\partial \mathbf{x}_p}{\partial \mathbf{r}} \frac{d\mathbf{r}}{dt} + \frac{\partial \mathbf{x}_p}{\partial \xi} \frac{d\xi}{dt} \quad \rightarrow \quad \dot{\mathbf{x}}_p = \mathbf{J}_p \mathbf{v} \]

\[ \mathbf{J}_p = \begin{bmatrix} \frac{\partial \mathbf{x}_p}{\partial \mathbf{r}} & \frac{\partial \mathbf{x}_p}{\partial \xi} \end{bmatrix} \]
Multi-image calibration

Use images from different poses of the calibration pattern:
\[ \mathbf{x}_p^i : \text{a set of images features extracted from the } i^{\text{th}} \text{ image:} \]

\[
\begin{bmatrix}
\dot{x}_p^1 \\
\dot{x}_p^2 \\
\vdots \\
\dot{x}_p^n
\end{bmatrix}
= \mathbf{J}_p
\begin{bmatrix}
\dot{r}_1 \\
\dot{r}_2 \\
\vdots \\
\dot{r}_n
\end{bmatrix}
\]

Jacobian:

\[
\mathbf{J}_p =
\begin{bmatrix}
\frac{\partial x_p^1}{\partial r^1} & 0 & \cdots & 0 \\
0 & \frac{\partial x_p^2}{\partial r^2} & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & 0 & \frac{\partial x_p^n}{\partial r^n}
\end{bmatrix}
\]

- extrinsic parameters
- Intrinsic parameters
Experimental validations

- Zeiss Auriga 60 SEM (Femto-ST) and Zeiss EVO LS 25 (ISIR)
- Magnification: 300x to 10,000x
- Medium and fast scan speeds
- Multi-scale calibration pattern: square size from 1 μm to 25 μm
  - Rotation around Z axis from 0° to 40°
  - Tilt from 0° to 8°

Multi-scale calibration pattern (Femto-ST)

Experimental images from Auriga 60 SEM (Femto-ST)
Experimental validations

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Multi-scale calibration pattern (Femto-ST)

Experimental images from Auriga 60 SEM (Femto-ST)
Experimental validations

Evolution of residual error

- **Green:** estimated (4) points positions
- **Yellow:** points reprojection computed from intrinsic & extrinsic parameters
Experimental results

- Spatial distortions insignificant

Estimated distortion parameters (Auriga 60 SEM)

<table>
<thead>
<tr>
<th>Magnification $M$ (x)</th>
<th>estimated distortion parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k$</td>
</tr>
<tr>
<td>500</td>
<td>-5.65x10^{-9}</td>
</tr>
<tr>
<td>2000</td>
<td>-3.67x10^{-10}</td>
</tr>
<tr>
<td>5000</td>
<td>-1.15x10^{-10}</td>
</tr>
</tbody>
</table>


Experimental results

- Spatial distortions insignificant
- Difficult to observe the motion along the depth direction
- Perspective projection is not validated

### Calibration results with perspective projection (Auriga 60 SEM)

<table>
<thead>
<tr>
<th>Magnification (x)</th>
<th>$Z_i$ ($\mu$m)</th>
<th>$P_x$</th>
<th>$P_y$</th>
<th>residual error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>15752.7</td>
<td>70168.0</td>
<td>70058.3</td>
<td>0.15</td>
</tr>
<tr>
<td>1000</td>
<td>22302.1</td>
<td>201505.3</td>
<td>199729.8</td>
<td>0.08</td>
</tr>
<tr>
<td>2000</td>
<td>6803.4</td>
<td>122073.3</td>
<td>122312.0</td>
<td>0.12</td>
</tr>
<tr>
<td>5000</td>
<td>2316.2</td>
<td>103917.4</td>
<td>105067.7</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Badly estimated Z position and intrinsic parameters


Experimental results

- Spatial distortions insignificant
- Difficult to observe the motion along the depth direction
- Perspective projection is not validated
- Parallel projection is validated

<table>
<thead>
<tr>
<th>Mag. $M$ (x)</th>
<th>$P_x/M$</th>
<th>$P_y/M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.00895</td>
<td>0.00888</td>
</tr>
<tr>
<td>1000</td>
<td>0.00898</td>
<td>0.00895</td>
</tr>
<tr>
<td>2000</td>
<td>0.00898</td>
<td>0.00904</td>
</tr>
<tr>
<td>5000</td>
<td>0.00897</td>
<td>0.00910</td>
</tr>
</tbody>
</table>

Ratio for parallel projections are constant


Outline

• SEM and calibration
• **Controlling the motion along the depth direction**
• Micro and nano-positioning by visual servoing
• SEM autofocusing
• Visual tracking and pose estimation
Observation along the depth direction

To obtain the depth information from microscopic images:

- Stereo vision [Tunell,11] [Fan,14]
- Using image sharpness information
  - Depth from focus [Nayar,94] [Subbarao,95]
  - Depth from defocus [Subbarao,94] [Ziou,01]

images acquired by Zeiss EVO LS 25 SEM (ISIR)
Observation along the depth direction

To obtain the depth information from microscopic images:

- Stereo vision [Tunell,11] [Fan,14]
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  - Depth from defocus [Subbarao,94] [Ziou,01]

To achieve visual servoing tasks along the depth direction:

- observing the image sharpness as a visual feature to perform the control law
Visual feature to control Z motion

- Sharpness function selection for microscopic images [Sun,05] [Rudnaya,10]
- derivative-based functions: gradient, Laplacian…
- statistical functions: variance, autocorrelation, histogram, entropy…
- transform-based functions: DFT, DWT…

- Use the norm of image gradient as a visual feature

\[
G = \sum_{x=0}^{M} \sum_{y=0}^{N} (\nabla I_x^2(x,y) + \nabla I_y^2(x,y))
\]
Image defocus model

- Using a general imaging model for SEM images [Nicolls, 97]

\[ I(x, y, Z) = I^*(x, y, Z^*) \ast f(x, y) \]

depends on \( |Z - Z^*| \) and SEM

\[ I(x, y, Z) = \sum_u \sum_v I^*(x - u, y - v, Z^*) f(u, v) \]

- Point spread function: using a Gaussian kernel

\[ f(x, y) = \frac{1}{2\pi \sigma^2} e^{-\frac{x^2 + y^2}{2\sigma^2}} \]

\( \sigma \) : Standard deviation of Gaussian kernel
Control law

- Visual feature: image gradient
  \[ G = \sum_{x=0}^{M} \sum_{y=0}^{N} (\nabla I_x^2(x, y) + \nabla I_y^2(x, y)) \]

- Cost function
  \[ \hat{Z} = \underset{Z}{\text{argmin}} \ (G(Z) - G^*)^2 \]

- Control law
  \[ v_z = -\lambda L_G^{-1}(G(Z) - G^*) \]

- Compute Jacobian
  \[ \dot{G} = L_G v_z \quad L_G = \frac{\partial G}{\partial \sigma} \frac{\partial \sigma}{\partial Z} \text{ approximated as a constant [Lai,92]} \]

- Derivative of the image gradient
  \[ \frac{\partial G}{\partial \sigma} = \sum_{x=0}^{M} \sum_{y=0}^{N} 2(\nabla I_x(x, y) \frac{\partial \nabla I_x(x, y)}{\partial \sigma} + \nabla I_y(x, y) \frac{\partial \nabla I_y(x, y)}{\partial \sigma}) \]
Experimental validation along depth direction

Magnification: 1000x
Outline

• SEM and calibration
• Controlling the motion along the depth direction
• Micro and nano-positioning by visual servoing
• SEM autofocusing
• Visual tracking and pose estimation
Hybrid visual servoing for 6-DoF positioning tasks

• Image sharpness information as a visual feature for the motion along the depth direction
• Image photometric information as a visual feature for other 5 DoFs
Image intensity as a visual feature

- Minimize the image intensity error \([\text{Collewet, TRO, 11}]\) between the desired image and current image:

\[
e_I(r) = I(r) - I^*(r^*)
\]

- Control law

\[
\dot{q} = -\lambda J_I^+ e_I
\]

- Time deviation of a pixel intensity \(I\) is

\[
\dot{I} = -\nabla I L_x v \text{ where } \nabla I = \begin{bmatrix} \frac{\partial I}{\partial x} & 0 \\ 0 & \frac{\partial I}{\partial y} \end{bmatrix}
\]

For a whole image

\[
\dot{I} = \begin{pmatrix} -\nabla I_{00} L_x \\
\vdots \\
-\nabla I_{MN} L_x \end{pmatrix} v = L_IV
\]

L. Cui, E. Marchand, S. Haliyo, S. Régnier. 6-DoF automatic micropositioning using photometric information. In IEEE/ASME Int Conf. on Advanced Intelligent Mechatronics, AIM’14, Pages 918-923, Besançon, July 2014.
Hybrid visual servoing

• use image intensity
• velocities along 5 DoFs:

\[ \dot{q} = -\lambda J_I^+ e_I \]

• for eye-to-hand visual servoing

\[ J_I = -L_I^c \tilde{V}_F^F \tilde{J}_n(q) \]

\( c \tilde{V}_F \) the spatial motion transform matrix (5 DoFs)
\( F \tilde{J}_n(q) \) the robot Jacobian (5 DoFs)

• use image gradient
• velocity along depth direction:

\[ \dot{Z} = -\lambda_z J_G^{-1} e_G(Z) \]

• Jacobian

\[ J_G = -L_G^c \tilde{V}_F^F \tilde{J}_n(Z) \]
Experimental setup

- Positioning stage
- SmarPod: 6-DoF parallel kinematics robot
- Travel range (by manufacturer):
  - Translation: +/- 6 mm for x,y; +/-3 mm for z
  - Rotation: +/- 8° mm for x,y; +/- 15° mm for z

- Vision sensor
- Optical microscope: Basler acA1600-60gm
- SEM: Zeiss EVO LS 25
Experimental validation using an optical microscope

Magnification: 60x

Experimental setup in a SEM

- Specimen:
  - Membrane (indium phosphide and silicon)
  - Calibration rig (gold and silicon)
  - MEMS (silicon and oxide)
Experimental validation with a SEM

Magnification: 1000x
Outline

- SEM and calibration
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- SEM autofocusing
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SEM autofocusing

- Autofocus
  - Correct device focus by automatically regulating the focus sets
- Challenges
  - Robust and fast SEM autofocusing scheme is required
  - SEM imaging is different from the optical camera imaging
SEM focusing geometry

- SEM components
- Condenser lens
- Objective aperture
- Objective lens
- (Electronic) Working distance $W$
SEM focusing geometry

- SEM components
- Condenser lens
- Objective aperture
- Objective lens
- (Electronic) Working distance $W$
SEM focusing geometry

- SEM components
- Condenser lens
- Objective aperture
- Objective lens
- (Electronic) Working distance $W$
SEM Autofocus approach

- **Objective**
  - Maximize the image sharpness by changing the working distance
- **Possible ways to reach the optimum of image sharpness**
  - Searching-based [Batten,00] [Rudnaya,09]: Fixed stepsize search, Fibonacci search…
  - Polynomial regression [Rudnaya,12]
  - On-line estimation [Marturi,13]
- **Designing a closed-loop control system**
  - Visual feature: image gradient
  - Control law

![Control diagram](image)
Control law

- Visual feature: image gradient

\[ G(W) = \sum_{x=0}^{M} \sum_{y=0}^{N} (\nabla I_x^2(x, y) + \nabla I_y^2(x, y)) \]

- Minimize the function

\[ \varepsilon(W) = \alpha e^{-\beta G(W)} - \gamma \]

- Working distance update:

\[ \dot{W} = -\lambda J_{\varepsilon}^{-1} \varepsilon \]

- Jacobian

\[ J_{\varepsilon} = \frac{\partial \varepsilon}{\partial W} \]

\[ = -(\varepsilon + \gamma) \beta J_G \]
Experimental validation

- Jeol JSM 820 SEM (Femto-ST)
  - magnification: 300x to 2000x
  - different scan speeds
- Specimen:
  - calibration rig
  - silicon micropart

Experimental validation

Experiments conducted at

- 200x magnification
  - 720 ns/pixel scan speed

- 400x magnification
  - 180 ns/pixel scan speed
  - 720 ns/pixel scan speed
Outline

• SEM and calibration
• Controlling the motion along the depth direction
• Micro and nano-positioning by visual servoing
• SEM autofocusing
• Visual tracking and pose estimation
Visual tracking and pose estimation in SEM

- CURRENT TRACKING ALGORITHM IN SEM
  - Template-based matching [Jasper, 10]
  - Active contours model [Sievers, 06] [Fatikow, 08]
  - CAD model-based matching [Kratochvil, 09] [Tamadazte, 10]

- CHALLENGES
  - Images could be blurred due to the motion along z axis
  - Difficult to estimate the depth information

- PROPOSED SOLUTION
  - Involve the defocus in the template-based matching approach
  - Estimate depth position from defocus information
Template-based tracking in presence of defocus blur

4-DoF motion tracking

- Template registration
- Transformation: \( w(x, \mathbf{p}), \mathbf{p} = (\theta, t_x, t_y) \)
- Defocus: Gaussian kernel \( f(x, \sigma) \)

\( \sigma \): standard deviation of Gaussian kernel
Template-based tracking in presence of defocus blur

4-DoF motion tracking

- Template registration
  - Transformation: \( w(\mathbf{x}, \mathbf{p}), \mathbf{p} = (\theta, t_x, t_y) \)
  - Defocus: Gaussian kernel \( f(\mathbf{x}, \sigma) \)
    \( \sigma \) : standard deviation of Gaussian kernel

- Minimize the dissimilarity between the appearance of the template and the current image at a certain position.

  Consider sum of squared differences (SSD):

  \[
  \hat{\mathbf{p}} = \underset{\mathbf{p}}{\text{arg min}} \sum_{\mathbf{x} \in W} (I(w(\mathbf{x}, \mathbf{p}), \sigma) - I^*(\mathbf{x}))^2
  \]

  \[
  \hat{\sigma} = \underset{\sigma}{\text{arg min}} \sum_{\mathbf{x} \in W} (G(I(w(\mathbf{x}, \mathbf{p}), \sigma)) - G(I^*(\mathbf{x})))^2
  \]

  \( G \) : norm of image gradient

  \[
  G = \sum_{x=0}^{M} \sum_{y=0}^{N} (\nabla I_x^2(x, y) + \nabla I_y^2(x, y))
  \]

  \( x-y \) translation \( t_x, t_y \)

  \( z \) rotation \( \theta \)

  Defocus blur level
Experiments on 4 DoFs

Medium scan speed
383 ms/frame

Fast scan speed
95 ms/frame

images acquired at

![Graph 1](Image)

![Graph 2](Image)
Partial pose estimation by image registration

- The projection $\mathbf{x} = (u, v, 1)^T$ of a point $\mathbf{wX} = (wX, wY, wZ, 1)^T$:
  \[ \mathbf{x} = K\Pi c^T w \mathbf{X} \]
  
  $K$: sensor intrinsic parameters estimated in calibration process
  $\Pi$: parallel projection matrix
  $c^T w$: sensor/object frame transformation to be estimated

- Estimate point position from warping
  \[ \hat{\mathbf{x}}_2 = \mathbf{R}\hat{\mathbf{x}}_1 + \mathbf{t} \]
  \[ \mathbf{R} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \]

- Minimize the error between the re-projected position and the estimated position using non-linear optimization
  \[ \hat{\mathbf{r}} = \arg \min_{\mathbf{r}} \sum_{i=1}^{N} (i\mathbf{x}(\mathbf{r}) - i\hat{\mathbf{x}})^2 \quad \mathbf{r} = (X, Y, \theta_Z) \]
Depth position estimation

- General idea: estimating depth position from image gradient
- Hidden Markov model

- Particle filter: Bayesian-based method
  - State: position on depth direction
    \[ S_k = F(S_{k-1}, \nu_{k-1}) \]
  - Observation: image gradient
    \[ O_k = H(S_k, \varepsilon_k) \]
Depth position estimation

- State evolution model

\[
S_k = \begin{pmatrix} Z_k \\ \dot{Z}_k \end{pmatrix} = \begin{pmatrix} 1 & \Delta t \\ 0 & \alpha \end{pmatrix} \begin{pmatrix} Z_{k-1} \\ \dot{Z}_{k-1} \end{pmatrix} + \begin{pmatrix} 0 \\ \beta \end{pmatrix} \nu_{k-1}
\]

- Observation: image gradient
  - approximate the relation between image gradient and depth position

\[
O_k = G(Z) = \frac{p_0 + p_1 Z + p_2 Z^2}{q_0 + q_1 Z + Z^2} + \varepsilon
\]

![Graph showing the relationship between Z (μm) and Image Gradient. The x-axis represents Z (μm) ranging from -200 to 250, and the y-axis represents Image Gradient ranging from 0.6 to 1.7. The graph includes a rational function and a set of red dots representing the data points.](image)
Depth position estimation

- State evolution model

\[ \mathbf{S}_k = \begin{pmatrix} Z_k \\ \dot{Z}_k \end{pmatrix} = \begin{pmatrix} 1 & \Delta t \\ 0 & \alpha \end{pmatrix} \begin{pmatrix} Z_{k-1} \\ \dot{Z}_{k-1} \end{pmatrix} + \begin{pmatrix} 0 \\ \beta \end{pmatrix} \nu_{k-1} \]

- Observation: image gradient
  - approximate the relation between image gradient and depth position

\[ \mathbf{O}_k = G(Z) = \frac{p_0 + p_1 Z + p_2 Z^2}{q_0 + q_1 Z + Z^2} + \varepsilon \]

- Prediction [Arulampalam, 02]

\[ p(S_k | O_{1:k}) \approx \sum_{i=1}^{N_p} \omega^i_k \delta(S_k - S^i_k) \]

\( \omega^i_k \) weight of particle \( i \) in \( k^{\text{th}} \) iteration

- Updating weights

\[ \omega^i_k \propto \omega^i_{k-1} e^{-\tau \varepsilon_k} \]

\( \varepsilon_k \) registration error
Experimental results

![Graphs showing experimental results](image)

Images acquired at...
Conclusion
Conclusion

**SEM Calibration**
- parallel projection validated
- distortions: insignificant

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Conclusion

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Visual tracking
- defocus & template matching
- depth estimation

Robot
Conclusion

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• using defocus information

SEM focus control
• control working distance

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SEM autofocus
- closed-loop control scheme

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International Conference on Robotics and Automation (ICRA), 2014
International Journal of Optomechatronics
International Journal of Optical and Micromachining Technologies (ISOT), 2015
Transactions of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science (TMECH), under review

International Conference on Robotics and Automation (ICRA), 2015
International Journal of Automation and Information (AIM), 2014
Perspective

- Visual servoing for micro/nano-positioning tasks
- More experimental validations
  - at high magnifications (e.g. 10,000x)
  - with different samples (3D objects, complex textures)
  - by new SEM and new robotic platform (Femto-ST)
- Depth direction motion control
  - frequency domain based method
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- Micro/nano-manipulation tasks by visual servoing
Thanks for your attention

Le Cui

Lagadic group

IRISA

http://www.irisa.fr/lagadic

January 26th, 2016