Acquisition and fusion of heterogeneous data sets via external references

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Content

- Motivation
- Origin of concept
- Technical concept
- Processing steps
- Practical tests
- Conclusion
Motivation

Fusion of data of arbitrary nature

- Different sensors
- Different resolution
- Different sensor characteristics
- Different surface characteristics
- Without impact onto the object
- With subpixel accuracy
- Mobile
Motivation

fringe projector

Laserscanner
Motivation

Acquisition Technologies

Spatial Technologies
- Electro-optical
- Optical

Spectral Technologies
- Color Imaging
- Multispectral Imaging
- Hyperspectral Imaging
- Spectro photometry
- CT
- x-radiography
- IR-reflectography

Physical Technologies
- Electrical
- Magnetical
- Radar
- ....
Motivation

spectral vs. spatial

ultraviolet photography source: http://katherineara.com

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Motivation

Data fusion becomes the more difficult the more content of data sets is differing
Often in particular those fusions are most valuable

-> a fusion strategy would help, which is independent from the object

-> therefore external references

spectral vs. spatial

ultraviolet photography source: http://katherineara.com
Origin of concept

**context:**

Industrial production is characterized by a wide use of automation techniques.

Automation needs

- Quality control
- Process control

\[\Rightarrow\] automation is supported by precise measurement techniques

© Kuka
Origin of concept

Need of Pose Determination for 3D measurement techniques

- optically:
  + • precise
  • flexibly to integrate
  -
  • Difficult for large volumes

- combined use of a robot an optical system:
  + • large volumes possible
  • flexibly to integrate
  -
  • robot has impact on accuracy
Origin of concept

Accuracy enhancement for robot based measurements

- Tracking of the robot effector
- Combine laser tracker and camera
- Observe targets by highly accurate calibrated cameras (>2)

Increase pos. accuracy of an instrument mounted on effector

Con: Limits by the intersection geometry, head must be orientated to cameras
Origin of concept

- tracking by image rays
- Observation of a target on the robot head
Origin of concept

- Extend the idea of the photogrammetric set up
- Observing the effector mounted on the robot head
- Effector has to be seen from any position of the robot
- System observe the position and orientation of effector
Technical concept

Adapt the robot based concept for applications in CH

Assuring

• High accuracy
• Mobility
• Flexibility
• Affordability
Technical concept
Technical concept

tracking cameras

acquisition system

surface under study
**Technical concept**

- $C_{Si}$ coordinate system of acquisition system i
- $C_{Cj}$ coordinate system of tracking camera j
- $C_O$ object coordinate system
Technical concept

Procedure

- Simulation (optional)
- Various calibration steps
- Determination of geometrical relations at the object
- Data acquisition for each optical instrument
- Internal data processing for each optical instrument
- Transformation of all data into the common coordinate system
Simulations

Why?

The geometrical quality depends on many factors, like:

- Size and shape of the tracking object
- Number & distribution of signals on the tracking object
- Number and distribution of points in the individual images
- Visibility of signals for all cameras
- Number and arrangement of tracking cameras
- Field of view of cameras
- Resolution of the image sensor
- Quality of image measurements
Simulations

How to handle this problem?

Use rules of thumb for the outline of a system design

• Allows to estimate, whether the required quality is principally possible
• Allows to realize the system, with a higher risk of deviation from the goals

Use existing, standardized / known set ups

• Gives a good base
• Is less flexible, as long as not so many practical examples are available

Use simulations for optimization of a system design

• Allows precisely to estimate, how the required quality is achieved
• Need appropriate tools (cinema4D (or similar), target detection, bundle adjustment)
Simulation example

Simulation goals
- Define tracking material.
- Define stable setups.
- Evaluate achievable tracking accuracy.

Define tracking material
- Need of target frame and characteristics:
  - dimensions: 500 mm × 500 mm × 500 mm.
  - number of targets: 56.
- 5 Mpx tracking cameras.
- 6 mm or 8 mm lenses.
Simulation example

Simulation steps
(a) Scene creation.
(b) Image generation.
(c) Noise addition.
(d) Bundle adjustment.

Noise
- Picture coordinates.
- Object coordinates.
- Tracking cameras position.
- Tracking cameras orientation.
Simulation example

<table>
<thead>
<tr>
<th>Acquisition system</th>
<th>External dimensions (mm × mm × mm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab-designed multispectral camera</td>
<td>270 × 320 × 180</td>
<td>5</td>
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<tr>
<td>FluxData multispectral camera</td>
<td>92 × 112 × 187</td>
<td>1.51</td>
</tr>
<tr>
<td>Gom Atos III</td>
<td>490 × 170 × 300</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Simulation example

<table>
<thead>
<tr>
<th>Tracking accuracy goal: half a pixel/voxel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition system</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>FluxData MSC</td>
</tr>
<tr>
<td>Gom Atos III</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Three configurations</th>
</tr>
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<tbody>
<tr>
<td>Configuration</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Sarcophagus</td>
</tr>
<tr>
<td>Wall-painting</td>
</tr>
<tr>
<td>Statue</td>
</tr>
</tbody>
</table>
Simulation example

For $d = 0.1 \text{ mm}$ and $D = 1 \text{ m}$
follows: $a = 0.0001$ or 0.1 mrad or 5.7 mGrad

$\frac{d}{D} = \frac{\alpha}{\rho}$

$\rightarrow$ required angular tracking quality increases with increasing distance $D$
$\rightarrow$ required positional tracking accuracy corresponds to quality requirement $d$
Simulation example

Configuration sarcophagus

sarcophagus at the minster St. Matthias at Trier

monitoring of the degradation of the sandstone
monitoring of change in colour
Simulation example

Configuration sarcophagus
Simulation example

Configuration sarcophagus
Simulation example

Configuration sarcophagus
Simulation example

Configuration sarcophagus

- Area of interest: $2 \, \text{m} \times 1.5 \, \text{m}$.
- 6 tracking cameras.
- Tracking setup:

(a) Front view

(b) Side view
Simulation example

Configuration statue

(a) Top view
(b) Front view
(c) Side view
Simulation example

Impact of configuration factors on accuracy: statue case

<table>
<thead>
<tr>
<th>Setup</th>
<th>Picture coordinates (pixel)</th>
<th>Object coordinates (µm)</th>
<th>Input noise</th>
<th>Output accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Orientation translation (mm)</td>
<td>Orientation rotation (mrad)</td>
</tr>
<tr>
<td>(a)</td>
<td>1/10</td>
<td>0.345</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(b)</td>
<td>1/10</td>
<td>0.345</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(c)</td>
<td>1/10</td>
<td>0.345</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>(d)</td>
<td>1/10</td>
<td>0.345</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>(e)</td>
<td>1/30</td>
<td>0.115</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

(a) Four cameras are used to track the full scene, only three for this subset.
(b) Eight cameras are used to track the full scene, only six are used in the simulations.
(c) Same as (b) with cameras vertically aligned instead of staggered.
(d) Same as (c) with realistic noise.
(e) Same as (c) with best-case scenario noise.
## Simulation example

**Impact of tracking object size on accuracy**

<table>
<thead>
<tr>
<th>Target frame dimensions (m x m x m)</th>
<th>Points</th>
<th>Output accuracy</th>
<th>See table</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Spatial (mm)</td>
<td>Angular (mrad)</td>
</tr>
<tr>
<td>(a) 0.5 x 0.4 x 0.3</td>
<td>26</td>
<td>0.015</td>
<td>0.144</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>0.012</td>
<td>0.124</td>
</tr>
<tr>
<td>(b) 0.5 x 0.5 x 0.5</td>
<td>26</td>
<td>0.017</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>0.012</td>
<td>0.088</td>
</tr>
</tbody>
</table>
Simulation example

<table>
<thead>
<tr>
<th>Simulation results</th>
<th>Tracking spatial (mm)</th>
<th>Accuracy angular (mrad)</th>
<th>Number of cameras</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FluxData MSC Gom Atos III</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>0.139</td>
<td>0.198</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>0.120</strong></td>
<td><strong>0.158</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sarcophagus (0.4 m \times 0.8 m)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>realistic</td>
<td>0.024</td>
<td>0.172</td>
<td><strong>4</strong></td>
</tr>
<tr>
<td></td>
<td><strong>0.014</strong></td>
<td><strong>0.100</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Wall-painting (2 m \times 1.5 m)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>realistic</td>
<td>0.032</td>
<td>0.216</td>
<td><strong>6</strong></td>
</tr>
<tr>
<td></td>
<td><strong>0.015</strong></td>
<td><strong>0.106</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Statue (1 m high, 0.6 m \ø)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>realistic</td>
<td>0.057</td>
<td>0.362</td>
<td><strong>8</strong></td>
</tr>
<tr>
<td></td>
<td><strong>0.019</strong></td>
<td><strong>0.122</strong></td>
<td></td>
</tr>
</tbody>
</table>

General aspect: angular precision is harder to meet

- target object should have a sufficient size (due to base to distance ratio effect)
Calibrations

- Tracking cameras interior orientation.
- Acquisition systems interior orientation.
- Target frame calibration.
- Target frame to acquisition system calibration.
Calibrations

- Tracking cameras interior orientation.
- Acquisition systems interior orientation.
- Target frame calibration.
- Target frame to acquisition system calibration.
Camera calibration

- For precise applications, it is important to know the internal geometry of a camera
- Typical parameter $c$, $x_h$, $y_h$, $a_1$, $a_2$, $a_3$, ...
- The process needs many & precise image measurements
- The parameter might keep stable for a time, but this is not sure
- -> calibrate for the acquisition you plan
Camera calibration

- Calibration object with numerous targets
- Pictures taken from different views
Calibrations

- Tracking cameras interior orientation.
- Acquisition systems interior orientation.
- Target frame calibration.
- Target frame to acquisition system calibration.
Calibration of acquisition system

• Similarly to the cameras also an acquisition needs to be known in his inner geometry
• The process depends on the acquisition system
  • System calibration (cf. active stereo systems)
  • Laboratory calibration (multispectral, hyperspectral cameras, thermal cameras…)
  • Classical camera calibration, if the system has a classical optical set up
• The data for calibration should be actual / needs to be redone
Calibrations

- Tracking cameras interior orientation.
- Acquisition systems interior orientation.
- Target frame calibration.
- Target frame to acquisition system calibration.

- Tracking cameras
- Acquisition systems
- Target frame
Target frame calibration

- The target frame carries important geometrical information as the tracking process uses the geometry to improve geometrical quality
- The target frame has to be stable
- Calibration can be done through an appropriate photogrammetric process
- The data for the geometry should be actual
- Demands for quality: high
Target frame calibration

![Target frame calibration](image)
Calibration process

- Tracking cameras interior orientation.
- Acquisition systems interior orientation.
- Target frame calibration.
- Target frame to acquisition system calibration.
Tracking object to acquisition system calibration

• The geometrical relation between tracking object and acquisition systems has to be done for each acquisition system
  • Reason: the tracking object provides the external reference, which is needed for each used acquisition system

• Possibility
  • Manual adjustment
  • Photogrammetric process

• Demands for quality: in the range of desired quality at the object
Target frame to acquisition system calibration
Determination of geometrical relations at the object

- Tracking cameras positioning.
- Tracking cameras exterior orientation.
- Simultaneous acquisitions by the acquisition systems and tracking cameras.
Determination of geometrical relations at the object

- Tracking cameras positioning.
- Tracking cameras exterior orientation.
- Simultaneous acquisitions by the acquisition systems and tracking cameras.
Determination of geometrical relations at the object

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Determination of geometrical relations at the object
Determination of geometrical relations at the object

- Tracking cameras positioning.
- Tracking cameras exterior orientation.
- Simultaneous acquisitions by the acquisition systems and tracking cameras.
Data acquisition for each optical instrument

- Tracking cameras positioning.
- Tracking cameras exterior orientation.
- Simultaneous acquisitions by the acquisition systems and tracking cameras.
Data acquisition for each optical instrument

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Data acquisition for each optical instrument

- Tracking cameras positioning.
- Tracking cameras exterior orientation.
- Simultaneous acquisitions by the acquisition systems and tracking cameras.
Internal processing for each optical instrument

Individually depends on type and characteristics of an optical instrument

Active stereo system: (fuse image data to a 3D model)
- Location & identification of pattern elements
- Solve correspondence
- Generate 3D data
- Blunder detection
- (Surface generation)

Multispectral system (transform raw data)
- Apply sensor calibration
- Calculate spectrum
- Calculate surface reflectance
- ...

Thermal camera (.....)
UV camera (.....)
.....
Transformation into the common coordinate system
Transformation into the common coordinate system
Transformation into the common coordinate system
Practical tests

Evaluation of tracking quality

Practical cases

- Car door (3D – 3D)
- Cross stitch canvas (3D – MS)
- Bas relief (3D – MS)
Practical tests

Stability of the target frame

<table>
<thead>
<tr>
<th></th>
<th>RMS of residuals</th>
<th>RMS of number</th>
<th>Number of images</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x (mm)</td>
<td>y (mm)</td>
<td>z (mm)</td>
</tr>
<tr>
<td>A</td>
<td>0.018</td>
<td>0.018</td>
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</tr>
<tr>
<td>B</td>
<td>0.013</td>
<td>0.013</td>
<td>0.014</td>
</tr>
<tr>
<td>C</td>
<td>0.014</td>
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<tr>
<td>D</td>
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<tr>
<td>E</td>
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<tr>
<td>F</td>
<td>0.011</td>
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<td>0.012</td>
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<tr>
<td>G</td>
<td>0.019</td>
<td>0.019</td>
<td>0.020</td>
</tr>
<tr>
<td>H</td>
<td>0.023</td>
<td>0.023</td>
<td>0.026</td>
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<tr>
<td>I</td>
<td>0.013</td>
<td>0.014</td>
<td>0.017</td>
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<tr>
<td>J</td>
<td>0.011</td>
<td>0.012</td>
<td>0.014</td>
</tr>
<tr>
<td>K</td>
<td>0.010</td>
<td>0.010</td>
<td>0.011</td>
</tr>
<tr>
<td>L</td>
<td>0.018</td>
<td>0.018</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Calibration results for 12 control measurements over time
Practical tests

Stability of the target frame

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>0.05</td>
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<td>B</td>
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<tr>
<td>D</td>
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<td>0.03</td>
<td>0.04</td>
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<td>J</td>
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<td>L</td>
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<td>0.05</td>
<td>0.04</td>
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<td>0.08</td>
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<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Average absolute difference in the point to point distances between the photogrammetric targets for every pair of target frame calibrations, in millimeters
Practical tests

Photogrammetric tracking vs. laser tracking

- Move target around
- Calculate position & orientation
- Transform to start position
- Compare signals

Laser tracker has reference accuracy
(depending on mode 0.003 mm vs. 0.020 mm)
## Practical tests

Photogrammetric tracking vs. laser tracking

<table>
<thead>
<tr>
<th>Position</th>
<th>Laser tracker Estimated</th>
<th>Photogrammetry Estimated</th>
<th>Internal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.038</td>
<td>0.053</td>
<td>0.015</td>
</tr>
<tr>
<td>2</td>
<td>0.046</td>
<td>0.105</td>
<td>0.020</td>
</tr>
<tr>
<td>3</td>
<td>0.038</td>
<td>0.083</td>
<td>0.024</td>
</tr>
<tr>
<td>4</td>
<td>0.041</td>
<td>0.049</td>
<td>0.020</td>
</tr>
<tr>
<td>5</td>
<td>0.029</td>
<td>0.063</td>
<td>0.015</td>
</tr>
<tr>
<td>6</td>
<td>0.033</td>
<td>0.040</td>
<td>0.019</td>
</tr>
<tr>
<td>7</td>
<td>0.026</td>
<td>0.033</td>
<td>0.021</td>
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<tr>
<td>8</td>
<td>0.026</td>
<td>0.048</td>
<td>0.022</td>
</tr>
<tr>
<td>9</td>
<td>0.026</td>
<td>0.039</td>
<td>0.022</td>
</tr>
<tr>
<td>10</td>
<td>0.029</td>
<td>0.062</td>
<td>0.020</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.033</strong></td>
<td><strong>0.058</strong></td>
<td><strong>0.020</strong></td>
</tr>
</tbody>
</table>

Estimated: comparison of tracking results  
Internal: adjustment result

**Result:**

- Tracking results are good
- Internal values are a bit optimistic (this is the normal case)

**Tracker is:**

- more homogenous  
- better in quality
Practical tests

Tracking with 6 cameras
Practical tests

Tracking with 6 cameras

Figure 4.18: Spatial and angular tracking accuracy when using six cameras, compared to the simulation results and to the target accuracy.

Blue / light blue : 4 cameras

Spatial accuracy (mm)

0,000 0,020 0,040 0,060 0,080 0,100 0,120 0,140

M1 M3 M5 M7 M9 M11 M13 M15

Angular accuracy (mrad)

0,000 0,050 0,100 0,150 0,200

M1 M3 M5 M7 M9 M11 M13 M15

Target: FluxData MSC
Target: Atos III
Target: lab-designed MSC
Simulations: realistic
Simulations: best-case
Practical tests

Summary for internal accuracy in different tests

- \( l_t \times \): laser tracker
- \( c_r \): car door
- \( b_r \times \): bas relief
- \( c_r \): cross-stitched canvas
Practical tests

Summary for accuracy tests:

- Geometrical quality meets requirements and principally confirms the results from simulations
- Positional accuracy is easier to achieve than the angular one
- Internal accuracy of photogrammetry is too optimistic
- The stability of the frame is important
- The camera configuration plays a significant role

-> results need to be checked in measurements at objects

Used test objects:
- Car door (3D – 3D)
- Cross stitch canvas (3D – MS)
- Bas relief (3D – MS)
Practical tests (3D – 3D)

Car door acquisitions

- Full dimensions: 1100 mm × 600 mm.
- Area of interest: 800 mm × 600 mm.
Practical tests (3D – 3D)

Figure 4.13: Spatial and angular tracking accuracy during the car door digitization, compared to the simulation results and to the target accuracy.
Practical tests (3D – 3D)

Pairwise comparison on target positions on the car surface

Accuracy at the object partly deviates strongly from the internal accuracy

Reason (after verification): the acquisition system was not completely stable inside tracking object during tracking
Practical tests (3D - MS)

Stitched canvas with 4 camera tracking
Practical tests (3D - MS)

3D acquisition for bas relief with 4 camera tracking
Practical tests (3D - MS)

Tracking positions (cross-stitch)  Tracking positions (bas relief)
Practical tests (3D - MS)

Spatial and angular tracking accuracy (cross-stitch)

FluxData accuracy is allowed to be lower (reduced acquisition distance)
Practical tests (3D - MS)

Spatial and angular tracking accuracy (bas relief)

FluxData accuracy is similar (comparable acquisition distance)
Practical tests (3D - MS)

Projection of MS data onto cross stitch canvas surface
Practical tests (3D - MS)

Projection of MS data onto bas relief surface
Practical tests (3D - MS)
Conclusions

External references provide a powerful solution

- combine data sets of any type and content
- work completely free from manipulations at the object
- work for textureless and also for morphological poor surfaces
- are able to achieve sub pixel accuracy
- are mobile

Have to be carefully applied

- stability aspects
- many orientation processes
- need experts (as long as no standards are developed)

Specific software necessary

Start to become available on the market (for industrial purposes)
Any questions?