Precise laser-based optical 3D measurement of welding seams under water
introduction

motivation:

• increasing constructions in seaports and offshore industry
• quality control
  • periodic inspections (ensure the safety of structures)
  • repair work (up to now: only single points inspected with a gauge)
• development of non-destructive testing techniques
  • detect surface defects
  • documentation
  • visual inspection

construction of an offshore wind turbine

underwater welding
• state of the art

• system concept

• measuring head

• experimental tests
  • tracking accuracy
  • profile measurements under water
  • different refraction indices

• summary and outlook
state of the art

- large variety of laser triangulation sensors
  - no green laser line, not for underwater use
  - cannot be calibrated by the user
  - accuracy: 0.1 mm – 0.5 mm
  - typical measurement range: 50 mm – 100 mm
- Creaform MaxScan
  - scanning of large surfaces, not for underwater use
  - accuracy: 0.1 mm – 0.5 mm
  - typical measurement range: without limitation (optical tracking)
- dense matching
  - purely image-based 3D surface registration
  - stereo image processing
  - only with enough surface texture
feasibility study:

- development of a measuring head for underwater applications
  - automatic measurement of weld geometry and surface topography with highest accuracy
  - laser-based
- optical tracking of a measuring head
  - space resection
  - position determination of profile lines in object coordinate system
specifications and problems

- demanded resolution for a feature (crack, pore): 0.1 – 0.5 mm

- overall accuracy of the system has to be better

- accuracy of the system depends on:
  - sensor resolution of the camera
  - configuration of camera and line laser
  - strategy of profile point estimation
  - calibration method
  - tracking method

- losses of accuracy because of the underwater problem:
  - visibility
  - multi-media model (refraction)
  - calibration
measuring head

calibration setting: photogrammetric object reference for calibration of the measuring head

tracking – accuracy analysis (air)

<table>
<thead>
<tr>
<th></th>
<th>BasProjekt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X [mm]</td>
</tr>
<tr>
<td>minimum</td>
<td>0.8</td>
</tr>
<tr>
<td>maximum</td>
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<tr>
<td>standard deviation</td>
<td>0.11</td>
</tr>
<tr>
<td>(repeatability)</td>
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</tr>
</tbody>
</table>

systematic deviations: 0.7 – 1.3 mm
- tracking component
- calibration, orientation errors

→ absolute positioning of all measured profiles
→ relative accuracy (in neighborhood) is better

→ under water: decrease in accuracy is expected
- lower image quality and resulting lower measurement quality
experimental tests – under water

measurement of objects under water

laptop for controlling of the measuring head

object reference with targeted points

aquarium with measuring object

measuring head

micrometer beat

laboratory setup
multi-media approach

principle of a simple multi-media correction

- ray tracing under consideration of the refraction index
- conditions:
  - cameras parameters
  - correct refraction indices \((n_i)\)
  - angle of impact and distance between cameras and glass medium \((L_i, N)\)

\[ L_{i+1} = n \cdot L_i + \left( n \cdot C - \sqrt{1 + n^2(C^2 - 1)} \right) \cdot N \]

\[ L_{i+1} = L_i \quad | \quad n = 1 \]

if root is negative
\(\rightarrow\) total reflection

\[ n = \frac{n_1}{n_2} \]

\[ C = -N \cdot L_i \]
results:
tracking under water – measurement of a contour artefact

- resolution of profiles ca. 0.1 mm
- width: 8 mm
- distance laser – welding seam: 150 mm

→ analysis of the features (radii, distances, angle)

3D point cloud of the contour artefact

orange: processing without multi-media correction
blue: processing with multi-media correction
tracking – measuring under water

results: differences

<table>
<thead>
<tr>
<th>feature</th>
<th>reference</th>
<th>air</th>
<th>underwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>cylinder_1</td>
<td>6.025 mm</td>
<td>0.009 mm</td>
<td>0.013 mm</td>
</tr>
<tr>
<td>cylinder_2</td>
<td>12.523 mm</td>
<td>-0.059 mm</td>
<td>-0.087 mm</td>
</tr>
<tr>
<td>cylinder_3</td>
<td>10.556 mm</td>
<td>-0.023 mm</td>
<td>0.015 mm</td>
</tr>
<tr>
<td>step1_1</td>
<td>0.499 mm</td>
<td>0.013 mm</td>
<td>0.000 mm</td>
</tr>
<tr>
<td>step1_2</td>
<td>0.996 mm</td>
<td>-0.013 mm</td>
<td>0.000 mm</td>
</tr>
<tr>
<td>step1_3</td>
<td>1.501 mm</td>
<td>-0.022 mm</td>
<td>0.036 mm</td>
</tr>
<tr>
<td>step1_4</td>
<td>2.007 mm</td>
<td>-0.004 mm</td>
<td>0.019 mm</td>
</tr>
<tr>
<td>step1_5</td>
<td>2.536 mm</td>
<td>-0.021 mm</td>
<td>0.037 mm</td>
</tr>
<tr>
<td>step1_6</td>
<td>3.002 mm</td>
<td>0.001 mm</td>
<td>0.033 mm</td>
</tr>
<tr>
<td>step2_1</td>
<td>0.991 mm</td>
<td>0.012 mm</td>
<td>0.021 mm</td>
</tr>
<tr>
<td>step2_2</td>
<td>1.002 mm</td>
<td>0.006 mm</td>
<td>0.026 mm</td>
</tr>
<tr>
<td>step2_3</td>
<td>0.998 mm</td>
<td>0.009 mm</td>
<td>0.012 mm</td>
</tr>
<tr>
<td>step2_4</td>
<td>1.002 mm</td>
<td>0.016 mm</td>
<td>0.017 mm</td>
</tr>
<tr>
<td>step2_5</td>
<td>1.011 mm</td>
<td>-0.006 mm</td>
<td>0.033 mm</td>
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<tr>
<td>step2_6</td>
<td>1.004 mm</td>
<td>0.027 mm</td>
<td>0.028 mm</td>
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<tr>
<td>step2_7</td>
<td>0.983 mm</td>
<td>-0.020 mm</td>
<td>0.007 mm</td>
</tr>
<tr>
<td>step2_8</td>
<td>0.992 mm</td>
<td>0.017 mm</td>
<td>0.014 mm</td>
</tr>
<tr>
<td>step2_9</td>
<td>2.510 mm</td>
<td>0.030 mm</td>
<td>0.044 mm</td>
</tr>
</tbody>
</table>

Mean accuracy: 0.022 mm

Mean accuracy: 0.035 mm
tracking – welding seam

tracking under water – welding seam
• resolution profile ca. 0.1 mm; width 20 mm
• distance laser – weld: ca. **160 mm**
tracking – welding seam

tracking under water – comparison between different resolutions

example of an underwater welded seam with small grooves

resolution: 0.1 mm: no detection of score marks

resolution: 0.05 mm: detection of grooves (another section of the weld)
repeated measurements

various test series

→ variation of water temperature and salinity
  → corresponding refraction indices from previous publications
  → deviations to current refraction index

→ results show relative deviations that still may be subject to systematic uncertainties in the refractive indices which have not been measured absolutely
repeated measurements

single measurement under water – repeated measurement

repeated measurement: differences to nominal value of the feature step height (temperature 20°C, salinity 0‰)

results:
- max. differences: 25µm
- standard deviation: 8µm
single measurements in salt water

Series 1: differences to nominal values
feature step height and radius with constant water temperature (20°C), salinity: 0% to 35%

<table>
<thead>
<tr>
<th>salinity [%]</th>
<th>temperature (20°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.33156</td>
</tr>
<tr>
<td>5</td>
<td>1.33247</td>
</tr>
<tr>
<td>10</td>
<td>1.33337</td>
</tr>
<tr>
<td>15</td>
<td>1.33428</td>
</tr>
<tr>
<td>20</td>
<td>1.33519</td>
</tr>
<tr>
<td>25</td>
<td>1.33609</td>
</tr>
<tr>
<td>30</td>
<td>1.33700</td>
</tr>
<tr>
<td>35</td>
<td>1.33791</td>
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</table>

- **step**: constant refraction index: 1.333
- **radius**: constant refraction index from table

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<thead>
<tr>
<th></th>
<th>step height</th>
<th>radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. difference corrected-uncorrected</td>
<td>20µm</td>
<td>28µm</td>
</tr>
<tr>
<td>noise</td>
<td>41µm</td>
<td>41µm</td>
</tr>
<tr>
<td>systematic deviation</td>
<td>15µm</td>
<td>14µm</td>
</tr>
<tr>
<td>standard deviation</td>
<td>16µm</td>
<td>16µm</td>
</tr>
</tbody>
</table>

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T. Ekkel, J. Schmik, T. Luhmann, H. Hastedt
Single measurements in salt water

Series 2: Differences to nominal value
feature step height and radius with constant salinity (35%); water temperature 10°C to 30°C

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Salinity 35%</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>Refraction index</td>
</tr>
<tr>
<td>10</td>
<td>1.33225</td>
</tr>
<tr>
<td>12</td>
<td>1.33215</td>
</tr>
<tr>
<td>14</td>
<td>1.33203</td>
</tr>
<tr>
<td>16</td>
<td>1.33189</td>
</tr>
<tr>
<td>18</td>
<td>1.33173</td>
</tr>
<tr>
<td>20</td>
<td>1.33156</td>
</tr>
<tr>
<td>22</td>
<td>1.33138</td>
</tr>
<tr>
<td>24</td>
<td>1.33118</td>
</tr>
<tr>
<td>26</td>
<td>1.33097</td>
</tr>
<tr>
<td>28</td>
<td>1.33075</td>
</tr>
<tr>
<td>30</td>
<td>1.33052</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncorrected</th>
<th>Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. difference corrected-uncorrected</td>
<td>19µm</td>
<td>37µm</td>
</tr>
<tr>
<td>Noise</td>
<td>58µm</td>
<td>50µm</td>
</tr>
<tr>
<td>Systematic deviation</td>
<td>30µm</td>
<td>27µm</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>21µm</td>
<td>17µm</td>
</tr>
</tbody>
</table>
summary

- development of a measuring head and a measuring concept
  - reconstruction of objects under water
- tracking results are within the specified measurement accuracy
  - accuracy tests of tracking: 0.1 mm
- evaluation of a simple multi-media approach
  - measuring a contour artefact
- measurements above water show very good results
  - mean accuracy: 0.022mm
- measurements of objects under water show also very good results
  - mean accuracy: 0.035mm
- corrections lead to better results with smaller noise or lower deviations to the reference values.
  - results are within our specified accuracy of 0.1 mm.
outlook

• tracking solution improvable
• simplified camera concept
• simple multi-media approach: suitability for real measurements is limited
  • future calibration concept: refraction index for water can be determined with high accuracy within a bundle adjustment
• realization of a underwater solution (camera housing) and diving-trips
• optimization of the measurement algorithms
Precise laser-based optical 3D measurement of welding seams under water

ISPRS/CIPA Workshop “Underwater 3D recording & modeling
Piano di Sorrento (Napoli), Italy
16. – 17. April 2015

Tanja Ekkel (M.Sc.)
Institute for Applied Photogrammetry and Geoinformatics (IAPG)
Jade University of Applied Sciences, Oldenburg
Germany
measurement process

1) • synchronous image acquisition with both calibrated camera systems

2) • calculation of epipolar geometry in images of stereo-laser profile system (find the epipolar line in image 2 corresponding to a point in image 1)

3) • detection of corresponding points (by searching on epipolar lines):
   • sub-pixel estimation by least-squares matching

4) • spatial intersection with multi-media correction: 3D profiles in the coordinate system stereo-laser profile system

5) • moving of stereo-laser profile system → tracking by tracking camera

6) • oriented profiles: 3D surface
experimental tests – tracking

tracking – accuracy analysis

- measurement process

object reference

\[ P(\mathbf{X}, \mathbf{Y}, \mathbf{Z}) \]

known point \( P \)

coordinate calculation

results of single point measurement
tracking – accuracy analysis

**tracking – accuracy analysis (air)**

<table>
<thead>
<tr>
<th></th>
<th>CamBar B2</th>
<th>Basler ace</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement distance</td>
<td>800 mm</td>
<td>150 mm</td>
</tr>
<tr>
<td>camera sensor</td>
<td>736 x 582</td>
<td>2048 x 2048</td>
</tr>
</tbody>
</table>

**BasProjekt**

<table>
<thead>
<tr>
<th></th>
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<th>Y [mm]</th>
<th>Z [mm]</th>
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<tr>
<td>minimum</td>
<td>0.8</td>
<td>-1.0</td>
<td>0.7</td>
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<td>1.15</td>
</tr>
<tr>
<td>standard deviation (repeatability)</td>
<td>0.11</td>
<td>0.09</td>
<td>0.11</td>
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systematic deviations: 0.7 – 1.3 mm

- tracking component
- calibration, orientation errors

→ absolute positioning of all measured profiles
→ relative accuracy (in neighborhood) is better

→ under water: decrease in accuracy is expected
- lower image quality and resulting lower measurement quality

used cameras:

- tracking component:
  - CamBar B2, Axios 3D Services
- measuring component:
  - ace, Basler AG

top view: principle of single point measurement; coordinates of point \( P \) are known