Calibration Quality

Comparing single trial registration matrix to "ground truth" registration matrix obtained from a combined 24 trials

1

Kuka→ Aruco Registration

- 29 calibration trials captures→ **5 for repeatability** +24 for registration matrix
- JSON Calibration
- Get registration matrix (source=JSON, target=aruco X24 trials)

2

Registration matrix (24 trials)

= GROUND TRUTH

```
----- LOAD Calibration Registration Matrix-------
----- Calibration Registration Matrix-------
[[ 9.70307596e-01 -2.36887572e-01  4.88615197e-02  5.15689627e-01]
 [ 4.76785513e-02 -1.07235591e-02 -9.98805167e-01  4.92143606e-01]
 [ 2.37128500e-01  9.71477886e-01  8.89305382e-04  8.05470266e-01]
 [ 0.00000000e+00  0.00000000e+00  0.00000000e+00  1.00000000e+00]]
```

3

Repeatability of Registration

- Take 5 Trials (4 positions each)
- Calculate their individual registration matrix T
- Get mean and std of each T component (for Rotation and translation matrices)
- Calculate their respective bias
- Calculate their respective TAE: total analytical error

***NOTE ALL IN standard units (Meters)

4

$$T^{aruco}_{kuka} = \begin{bmatrix} R_{00} & R_{01} & R_{02} & T_{03} \\ R_{10} & R_{11} & R_{11} & T_{13} \\ R_{20} & R_{21} & R_{21} & T_{23} \\ R_{30} & R_{31} & R_{31} & T_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Registration matrix obtained from 24 trials = "Ground Truth"

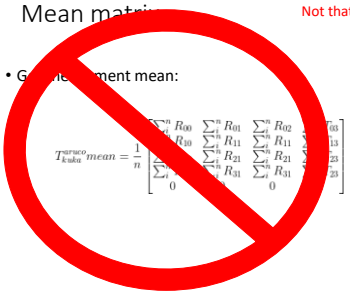
$$T^{aruco}_{kuka,trial=i} \begin{bmatrix} R_{00} & R_{01} & R_{02} & T_{03} \\ R_{10} & R_{11} & R_{11} & T_{13} \\ R_{20} & R_{21} & R_{21} & T_{23} \\ R_{30} & R_{31} & R_{31} & T_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Get registration matrix for each of the 5 trials used for repeatability.
→ Get their combined component means and std.
→ Compare with ground truth

5

Mean matri

Not that intuitive!



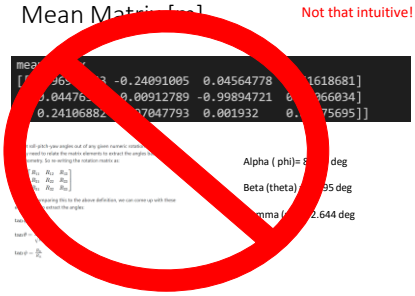
- G ment mean:

$$T^{aruco}_{kuka}\,mean = \frac{1}{n} \begin{bmatrix} \sum_i^n R_{00} & \sum_i^n R_{01} & \sum_i^n R_{02} & T_{03} \\ \sum_i^n R_{10} & \sum_i^n R_{11} & \sum_i^n R_{11} & T_{13} \\ \sum_i^n R_{20} & \sum_i^n R_{21} & \sum_i^n R_{21} & T_{23} \\ \sum_i^n R_{30} & \sum_i^n R_{31} & \sum_i^n R_{31} & T_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

6

Mean Matri

Not that intuitive!



7

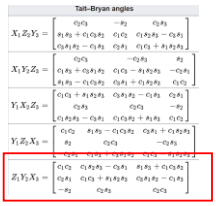
- Rotation matrix elements are not intuitive→ get equivalent roll,pitch, yaw angles for analysis
- Get row, pitch, yaw for every single trial
- Get mean and standard deviation
- Mean, and Standard deviation of tx,ty,tz

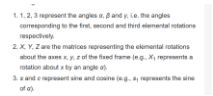
8

Rotation R convention

R= product of “3 elemental rotation matrices”:

ZYX Euler angles (roll, pitch, yaw)




1. 1, 2, 3 represent the angles α, β and γ, i.e. the angles corresponding to the first, second and third elemental rotations respectively.
2. X, Y, Z are the matrices representing the elemental rotations about the axes x, y, z of the fixed frame (e.g., X_1 represents a rotation about x by an angle α).
3. s and c represent sine and cosine (e.g., s_1 represents the sine of α).

https://en.wikipedia.org/wiki/Euler_angles

9

Roll, pitch, yaw Stats in deg

```
---- Mean Roll, pitch, yaw in Degree---------
89.88598465 13.94998535  2.64366285]
---- STD Roll, pitch, yaw in Degree---------
0.12825733 0.40497702 0.23202181]
```

- From each trial’s registration matrix, get the roll, pitch, yaw angles (degrees) from its rotation matrix

➔ Calculate mean and std over the 5 trials

12

Translation Stats in mm

```
----- Mean Translations [mm]---------
[516.18681283 490.66033575 805.75694641]
----- STD Translations [mm]---------
[1.85007297 1.77898862 3.17776836]
```

13

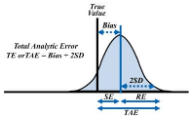
Not that intuitive!

14

TAE

1) Calculate Bias for translation and angles
2) Calculated TAE

*** Ground Truth is the Calibration Registration Matrix, and its corresponding angles, derived from 24 trials!



15

TAE

- Includes imprecision and trueness (bias) [1]
- TE (total error, a.k.a. total analytical error) – The sum of random error (imprecision) and systematic error (bias or inaccuracy). [2]

16

Ground Truth

```
-----  Calibration Registration Roll, Pitch, Yaw in Degrees-------
(89.9475506014213, 13.717123869291916, 2.813112386178329)
-----  Calibration Registration Translation in mm-------
[515.6896274  492.14360628 805.47026631]
```

17

TAE

Angles [deg]

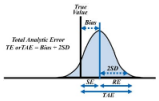
```
-------ANGLE BIAS Measurement in DEG---------
[ 0.06156595 -0.23286148  0.16944053]
-------Total Analytical Error Angles in DEG---------
[0.31808061 0.57709257 0.63349315]
```

Translation [mm]

```
-------Translation BIAS Measurement in mm---------
[-0.49718544  1.48327053 -0.2866801 ]
-------Total Analytical Error Translation in mm---------
[3.2029685  5.04124778 6.06885663]
```

18

GT and TAE all together




```
-----  Calibration Registration Roll, Pitch, Yaw in Degrees-------
(89.9475506014213, 13.717123869291916, 2.813112386178329)
-----  Calibration Registration Translation in mm-------
[515.6896274  492.14360628 805.47026631]
```

```
-------ANGLE BIAS Measurement in DEG---------
[ 0.06156595 -0.23286148  0.16944953]
-------Total Analytical Error Angles in DEG---------
[0.31808861 0.57709257 0.63349315]
```

```
-------Translation BIAS Measurement in mm---------
[-0.49718544  1.48327053 -0.2866801 ]
-------Total Analytical Error Translation in mm---------
[3.2029605  5.04124778 6.06885663]
```

Takeaways:
Both translation and rotation obtained from single trial (only 4-point 3D coordinates) have a low bias
TAE of Translation is however higher

➔ Improved kuka to realsense calibration should use more than 4 points to obtain the registration matrix.
➔ Evalutaion of position and tracking will thus be done using the 24 trials based registration matrix. Future recommendations: optimize the registration precision and accuracy .

19