Geometric and Stiffness Modeling and Design of Calibration Experiments for the 7 dof Serial Manipulator KUKA iiwa 14 R820

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Introduction

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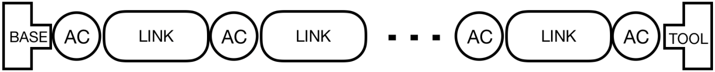
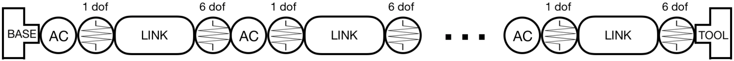
- Construction of the stiffness modeling using VJM (Virtual Joint Modeling) and MSA (Matrix Structural Analysis).
- The optimal pose selection is usually used for planar manipulators, our work was to extend the approach for a more complicated manipulator the KUKA iiwa 14 R820
- Building the complete and irreducible model for the 7 dof serial manipulator and performing the calibration

Elastostatic Modeling

- Model approximation of the manipulator



- VJM model

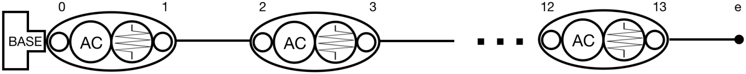


- This VJM model corresponds to the following extended model equation:

$$T_{ext} = T_{base} \cdot R_{z,q_1} \cdot R_{z,\theta_1} \cdot T_{z,d_1} \cdot H_{3D,\theta_7} \cdot R_{x,q_2} \cdot R_{x,\theta_8} \cdot T_{z,d_2} \cdot H_{3D,\theta_{14}} \cdot R_{z,q_3} \cdot R_{z,\theta_{15}} \cdot T_{z,d_3} \cdot H_{3D,\theta_{21}} \cdot R_{x,q_4} \cdot R_{x,\theta_{22}} \cdot T_{z,d_4} \cdot H_{3D,\theta_{28}} \cdot R_{z,q_5} \cdot R_{z,\theta_{29}} \cdot T_{z,d_5} \cdot H_{3D,\theta_{35}} \cdot R_{x,q_6} \cdot R_{x,\theta_{36}} \cdot T_{z,d_6} \cdot H_{3D,\theta_{42}} \cdot R_{z,q_7} \cdot R_{z,\theta_{43}} \cdot T_{Tool}$$

Elastostatic Modeling

- MSA model



- The details for each joint modeling is depicted below: The details for each joint modeling is depicted below:
    1. Elastic support 0,1:

$$\lambda^{r}_{*01} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \lambda^{e}_{*01} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Elastostatic Modeling

- Elastic joints with rotation about x-axis 2,3 6,7 10,11:

$$\lambda^r_{*ij} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \lambda^e_{*ij} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

- Elastic joints with rotations about the z-axis 4,5 8,9 12,13:

$$\lambda^r_{*ij} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \lambda^e_{*ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Calibration of the 7dof KUKA iiwa 14 R820

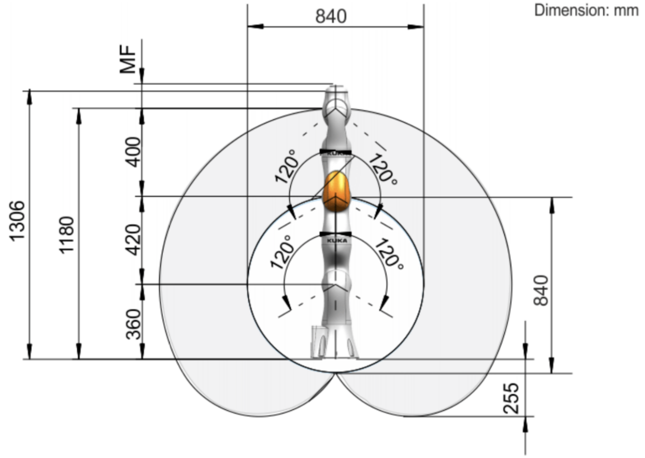
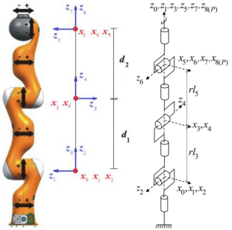


Figure: LBR iiwa 14 R820 working envelope, side view

Calibration of the 7dof KUKA iiwa 14 R820

- The complete and irreducible model in the form of homogeneous matrix product

$$
\begin{aligned}
T_{robot} = {} & R_z(q_1)\cdot T_x(\Delta l_{1x})\cdot T_y(\Delta l_{1y})\cdot R_y(\Delta q_{1y})\cdot R_x(q_2+\Delta q_2)\cdot T_y(\Delta l_{2y}) \\
& \cdot T_z(d_1+\Delta l_{2z})\cdot R_y(\Delta q_{2y})\cdot R_z(q_3+\Delta q_3)\cdot T_x(\Delta l_{3x})\cdot T_y(\Delta l_{3y})\cdot Ry(\Delta q_{3y}) \\
& \cdot R_x(q_4+\Delta q_4)\cdot T_y(\Delta l_{4y})\cdot T_z(d_2+\Delta l_{4z})\cdot R_y(\Delta q_{4y})\cdot R_z(q_5+\Delta q_5) \\
& \cdot T_x(\Delta l_{5x})\cdot T_y(\Delta l_{5y})\cdot R_y(\Delta q_{5y})\cdot R_x(q_6+\Delta q_6)\cdot T_y(\Delta l_{6y})\cdot T_z(\Delta l_{6z}) \\
& \cdot R_y(\Delta q_{6y})\cdot R_z(q_7)
\end{aligned}
$$

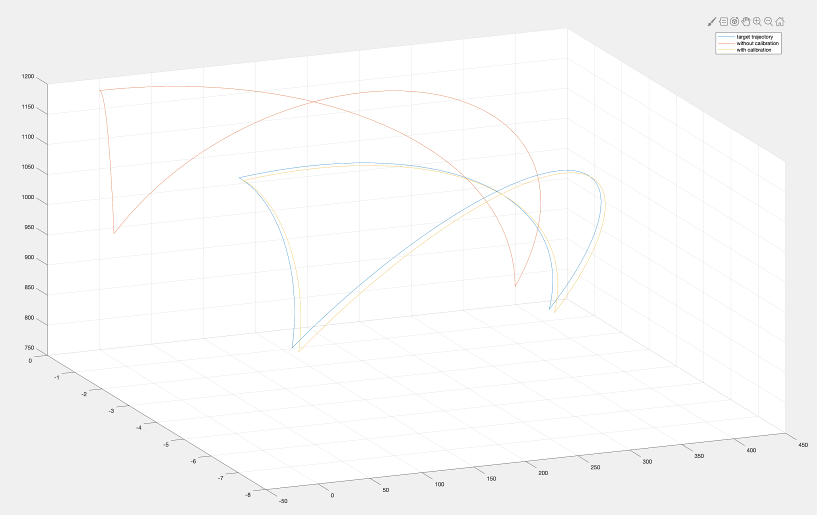


Calibration of the 7dof KUKA iiwa 14 R820

Parameters Identification

Parameter	Real value	Calibration	No Calibration	Improvement Factor
p_{x1}	-0.0051	-0.0088	0.0000	1.37
p_{y1}	-0.0023	0.0187	0.0000	1.10
ϕ_{y1}	-0.0049	-0.0049	0.0000	236.95
Δq_2	0.0089	0.0088	0.0000	178.35
p_{y2}	-0.0058	-0.0380	0.0000	0.17
p_{2z}	423.8028	423.7902	420.0000	301.81
ϕ_{y2}	-0.0023	-0.0024	0.0000	56.69
Δq_3	-0.0058	-0.0058	0.0000	500.43
p_{x3}	0.0074	-0.0046	0.0000	0.61
p_{y3}	-0.0097	-0.0132	0.0000	2.82
ϕ_{y3}	-0.0052	-0.0052	0.0000	76.20
Δq_4	0.0036	0.0035	0.0000	45.79
p_{y4}	0.0035	-0.0196	0.0000	0.15
p_{z4}	399.3576	399.3678	400.0000	62.98
ϕ_{y4}	-0.0050	-0.0050	0.0000	127.71
Δq_5	0.0063	0.0064	0.0000	62.00
p_{x5}	-0.0046	-0.0283	0.0000	0.18
p_{y5}	-0.0057	-0.0111	0.0000	1.03
ϕ_{y5}	$6.762e^{-4}$	0.0007	0.0000	12.81
Δq_6	0.0023	0.0024	0.0000	22.00
p_{y6}	0.0048	0.0096	0.0000	1.00
p_{z6}	0.0048	0.6044	0.0000	0.00
ϕ_{y6}	-0.0041	-0.0041	0.0000	201.38
base x	0.0000	-0.0098	0.0000	0.00
base y	0.0000	-0.0192	0.0000	0.00
base z	365.5582	365.5518	360.0000	537.78
tool 1x	0.0000	0.0030	0.0000	0.00
tool 1y	0.0000	-0.0111	0.0000	0.00
tool 1z	89.6944	89.0951	90.0000	0.50
tool 2x	0.0000	-0.0014	0.0000	0.00
tool 2y	-77.5044	-77.5058	-77.9423	336.76
tool 2z	-44.7472	-45.3375	-45.0000	0.42
tool 3x	0.0000	0.0204	0.0000	0.00
tool 3y	78.6892	78.6877	77.9423	497.93
tool 3z	-45.4312	-46.0641	-45.0000	0.68
		Average:		93.36

Calibration of the 7dof KUKA iiwa 14 R820



Design of Calibration Experiments

- Optimal plan for 4-link manipulator using 4 measurements configurations

4-link manipulator

***n* = 4**

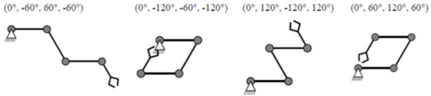
m = 4

$$
\begin{array}{llll}
q_1^1 = \alpha_1; & q_2^1 = \beta_1; & q_3^1 = \gamma; & q_4^1 = \delta \\
q_1^2 = \alpha_2; & q_2^2 = \beta_1 + \pi; & q_3^2 = \gamma; & q_4^3 = \delta + \pi \\
q_1^3 = \alpha_3; & q_2^3 = \beta_2; & q_3^3 = \gamma + \pi_2; & q_4^3 = \delta + \beta - \beta_2 \\
q_1^4 = \alpha_4; & q_2^4 = \beta_2 + \pi; & q_3^4 = \gamma + \pi_2; & q_4^4 = \delta + \beta - \beta_2 + \pi
\end{array}
$$

4-link manipulator

***n* = 4**

m = 4



Design of Calibration Experiments

- Optimal plan for the entire manipulator using 16 measurements configurations

q_1	q_2	q_3	q_4	q_5	q_6	q_7
α_1	ϵ_1	β_1	χ	γ	ϕ	δ
α_1	$\epsilon_1+\pi$	β_1	χ	γ	$\phi+\pi$	δ
α_1	ϵ_2	β_1	$\chi+\pi$	γ	$\phi+\epsilon_1-\epsilon_2$	δ
α_1	$\epsilon_2+\pi$	β_1	$\chi+\pi$	γ	$\phi+\epsilon_1-\epsilon_2+\pi$	δ
α_2	ϵ_1	$\beta_1+\pi$	χ	γ	ϕ	$\delta+\pi$
α_2	$\epsilon_1+\pi$	$\beta_1+\pi$	χ	γ	$\phi+\pi$	$\delta+\pi$
α_2	ϵ_2	$\beta_1+\pi$	$\chi+\pi$	γ	$\phi+\epsilon_1-\epsilon_2$	$\delta+\pi$
α_2	$\epsilon_2+\pi$	$\beta_1+\pi$	$\chi+\pi$	γ	$\phi+\epsilon_1-\epsilon_2+\pi$	$\delta+\pi$
α_3	ϵ_1	β_2	χ	$\gamma+\pi$	ϕ	$\delta+\beta_1-\beta_2$
α_3	$\epsilon_1+\pi$	β_2	χ	$\gamma+\pi$	$\phi+\pi$	$\delta+\beta_1-\beta_2$
α_3	ϵ_2	β_2	$\chi+\pi$	$\gamma+\pi$	$\phi+\epsilon_1-\epsilon_2$	$\delta+\beta_1-\beta_2$
α_3	$\epsilon_2+\pi$	β_2	$\chi+\pi$	$\gamma+\pi$	$\phi+\epsilon_1-\epsilon_2+\pi$	$\delta+\beta_1-\beta_2$
α_4	ϵ_1	$\beta_2+\pi$	χ	$\gamma+\pi$	ϕ	$\delta+\beta_1-\beta_2+\pi$
α_4	$\epsilon_1+\pi$	$\beta_2+\pi$	χ	$\gamma+\pi$	$\phi+\pi$	$\delta+\beta_1-\beta_2+\pi$
α_4	ϵ_2	$\beta_2+\pi$	$\chi+\pi$	$\gamma+\pi$	$\phi+\epsilon_1-\epsilon_2$	$\delta+\beta_1-\beta_2+\pi$
α_4	$\epsilon_2+\pi$	$\beta_2+\pi$	$\chi+\pi$	$\gamma+\pi$	$\phi+\epsilon_1-\epsilon_2+\pi$	$\delta+\beta_1-\beta_2+\pi$

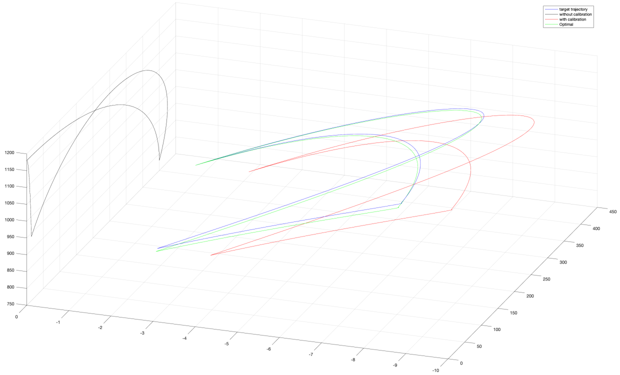
Design of Calibration Experiments

Design of experiments

Parameter	Real value	Optimal Plan	Random Plan	Improvement Factor
p_{x1}	0.0063	0.0003	0.0034	0.48
p_{y1}	0.0081	0.0003	0.0156	0.96
ϕ_{y1}	-0.0075	2.1908e-06	-0.0074	0.01
Δq_2	0.0083	0.00060	0.0083	0.00
p_{y2}	0.0026	-0.0488	0.0128	0.20
p_{2z}	415.9754	415.9700	415.9723	0.57
ϕ_{y2}	-0.0044	-0.0044	-0.0045	2.41
Δq_3	0.0009	0.0010	0.0009	0.00
p_{x3}	0.0092	0.0141	-0.0045	2.82
p_{y3}	0.0093	0.0069	0.0088	0.21
ϕ_{y3}	-0.0068	-0.0070	-0.0068	0.00
Δq_4	0.0094	0.0094	0.0094	0.00
p_{y4}	0.0091	0.0096	0.0160	12.90
p_{z4}	399.8538	399.8500	399.8661	3.24
ϕ_{y4}	0.0060	0.0062	0.0059	0.48
Δq_5	-0.0072	-0.0072	-0.0072	0.00
p_{x5}	-0.0016	-0.0002	-0.0120	7.21
p_{y5}	0.0083	0.0146	0.0112	0.46
ϕ_{y5}	0.0058	0.0058	0.0059	2.87
Δq_6	0.0092	0.0092	0.0091	31.25
p_{y6}	0.0031	0.0093	0.0054	0.37
p_{z6}	-0.0093	0.0038	-1.7009	129.28
ϕ_{y6}	0.0070	0.0069	0.0069	0.67
base x	0.0000	0.0004	0.0223	60.06
base y	0.0000	0.0003	0.0011	3.56
base z	364.3399	0.0000	364.3303	0.00
tool 1x	0.0000	0.0006	-0.0009	1.48
tool 1y	0.0000	-0.0488	0.0138	0.28
tool 1z	89.6944	415.9700	91.3873	0.01
tool 2x	0.0000	-0.0044	-0.0005	0.11
tool 2y	-77.5044	0.0010	-77.5138	0.00
tool 2z	-44.7472	0.0141	-43.0611	0.04
tool 3x	0.0000	0.0069	0.0084	1.21
tool 3y	78.6892	-0.0070	78.7003	0.00
tool 3z	-45.4312	0.0094	-43.7463	0.04
		Average:		7.52

Design of Calibration Experiments

- Trajectory obtained before and after calibration (using optimal and random plan)



https://youtu.be/_Ag43JsTvqA

Conclusions

- The project present the stiffness modeling and the design of calibration experiment for the spatial anthropomorphic manipulator KUKA iiwa 14 R820.
- For the stiffness modeling we used two approaches to build the cartesian stiffness matrix namely VJM and MSA modeling.
- For the calibration, using wise decomposition of the manipulator structure into two planar serial sub-chains, we were able to build 16 measurements configurations describing the optimal pose
- The complete and irreducible model of the robot was established to perform the calibration simulation, the latter showed clear improvement in the parameters identification with the optimal plan obtained which confirms the efficiency of the approach used.