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Joint Stiffness Analysis for Robot Calibration

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1. Introduction

Kinematic calibration used to be effective for many industrial robot applications in case that robot deflection to the load is small enough. However, when a robot carries the heavy load, the joint deflection effect has become a significant role in the robot's accuracy. In this paper, the joint stiffness analysis for the robot calibration has been done to show how much effectiveness the stiffness calibration shows according to the variations of the load.

This paper is going to present a simulation analysis of joint stiffness based calibration. In section 3.1, we concerns about the joint stiffness calibration algorithm be used in joint stiffness based calibration. In section 3.2, we consider about joint stiffness based calibration simulation for a serial manipulator and we also show how well the stiffness calibration algorithm is base on the result we got. The last sections are conclusionand reference. All result tables are put in the appendix section.

2. JOINT STIFFNESS BASED CALIBRATION ALGORITHM AND SIMULATION ANALYSIS.

3.1) Iterative linear least square algorithm applied in joint stiffness based calibration.

A Six DOF serial manipulator has 24 parameters need to be calibrated. We got 20 tip points of end effector and encoder values of six joints according to 20 robot's poses. Doing the forward kinematic calculation we get the coordinates of tip point of end effector.

$$\Delta X = X_{computed} - X_{measured}$$

$$\Delta X = \Delta X_{Kinematic} + \Delta X_{Deflection}$$

$$\Delta X = \left[J_{\Phi} + J_{\theta}[T] \right] \begin{bmatrix} \Delta\Phi' \\ c \end{bmatrix}$$

$$C^{i} = J_{\Phi} + J_{\theta}.[T_{i-1}]$$

Where, c_i_compliance of joint i^{th}; c_compliance vector contains c_i elements; [T]: joint torque matrix; J_{Φ}, J_{θ}, C Jacobian matrices.

+ $\Delta X^{i} = C^{i}.\Delta\Phi^{i}$
+ $\Delta\Phi^{i} = \left[\left(C^{i}\right)^{T}.C^{i} \right]^{-1} \left(C^{i}\right)^{T}.\Delta X^{i}$ (least square solution)
+ $\Phi^{i+1} = \Phi^{i} + \Delta\Phi^{i}$
+ $c_i \rightarrow T_i$

3.2) Joint stiffness based calibration simulation analysis.

Doing data generating to make a twenty points set include these following steps. Forward kinematic calculation with robot's real parameters. Then deflection calculation with robot's real parameters to get real position of end effector tip. After generating data, we calculated two indices. First one is data average error which is defined as average of 20 distances from real and nominal of end effector tip points. Second one is data max error which is defined as the biggest distance value among of 20 distances from real and nominal of end effector tip points. We assumed this set is the measured set which is taken from a manipulator's workstation.

In initial condition, we assumed that manipulator is changed in geometrical dimensions and has deflection with fairly heavy load. In other hand, we can say there are two sources of error, one comes from geometrical link dimensions and another comes from robot joint deflection. The result of kinematic calibration is shown in Res ult A-1. Comparing the calibrated parameters in Result A-1 and real parameters table 1 show us calibrated parameters approach the real parameters with a certain acceptable error 0.007 in average and 0.196 in maximum. However, this result just satisfy the least square algorithm and it does not really approach real parameters. If we applied the joints stiffness based calibration then we got the result in Result a-1 with very small error $5.5484 x 10^{-005}$ mm and calibrated parameters is nearly the same with robot 's real parameters. This simulation assure that the helpfulness of applying joints stiffness based calibration algorithm.

Now we consider the case A which data is generated with an assuming five joints deflected. The Result a-2 shows that the error is still bigger than the Result a-1 but smaller than only kinematic calibration case. And we also have a comparing between kinematic calibration Result A-1 with Results a-3, a-4 of joint stiffness based calibration is better. So we can give some evaluation in using joint stiffness based calibration is more effective than only kinematic calibration. Even in the Result a-5, the errors are equal to kinematic calibration errors but the different values between the real parameters and the calibrated parameters are smaller than the only kinematic calibration case. We consider the case B which data is generated with two joints deflected. We applied the joint stiffness algorithm and we got Result b-1, the result is nearly the same with robot 's real parameters, the error is very small. Comparing with the only kinematic calibration case table B-1 error 0.069, this comparison have a significant meaning. We now consider with anther case which result is Result b-2, in this case we though that the deflection come from five joints, the gotten results are negative stiffness value $K4 < 0$, $K5 < 0$. This result has no physical meaning, but we can explain that these stiffness value must be negative to satisfy least square algorithm and error of this case is very small 0.002 mm and calibrated parameters is nearly the same with real parameters of robot. This analysed case again assure that this joint stiffness algorithm 's effectiveness in carry out the actual robot parameters throught calibration.

4. CONCLUSION

Applying joint stiffness based calibration algorithm in identifying actual parameter values of a certain robot, the result of this simulation shows this is an effective method to calibrate a manipulator. After applying this joint stiffness based calibration algorithm, we got the result of parameters calibrated more accurate than only kinematic calibration.

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APPENDIX

Table 1 Real robot parameters

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.0175	0.0080	0.0175	0.0070	0.0040	1
2	-1.5848	0.0050	0	0	0	0.2
3	0.0175	0.4350	0	0	0.1520	1
4	-1.5830	0.0680	0	0	0.4650	0.5
5	1.5882	0.0030	0	0	0.0010	0.4
6	-1.5795	0.0040	0	0	0.0100	0
7	0	0.0220	0	-0.0220	0.1460	0

Table 2 Nominal robot parameters

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0	0	0	0	0	0
2	-1.5708	0	0	0	0	0
3	0	0.4320	0	0	0.1490	0
4	-1.5708	0.0600	0	0	0.4600	0
5	1.5708	0	0	0	0	0
6	-1.5708	0	0	0	0.0100	0
7	0	0.0200	0	-0.0180	0.1500	0

Result A-1. Robot's calibrated parameters under kinematic calibration only. Kin Average Error = 0.071332 [mm]; Kin Maximum Error = 0.1969 [mm]

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.017688	0.007972	0.07257	0.006988	0.003716	0.99754
2	-1.5847	0.004888	0	0	0	0.20322
3	0.017429	0.43492	0	0	0.1519	0.98208
4	-1.5829	0.067896	0	0	0.46492	0.50488
5	1.5883	0.002977	0	0	0.000962	0.40254
6	-1.5794	0.004062	0	0	0.01	0
7	0	0.021998	0	-0.021981	0.14602	0

Result B-1. Robot's calibrated parameters under kinematic calibration only. Kin Average Error = 0.068953 mm; Kin Maximum Error = 0.19625 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.017705	0.007967	0.017259	0.006986	0.003729	0.99669
2	-1.5847	0.004890	0	0	0	0.20344
3	0.017404	0.43492	0	0	0.15187	0.98086
4	-1.5828	0.067883	0	0	0.46493	0.50261
5	1.5884	0.002971	0	0	0.000992	0.40772
6	-1.5796	0.004069	0	0	0.01	0
7	0	0.021994	0	-0.02198	0.14602	0

Result a-1. Robot's calibrated parameters with five joints 2,3,4,5,6 considered. Average Error = 5.5484e-005 mm; Maximum Error = 0.00014578 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.0175	0.008	0.0175	0.007	0.004	1
2	-1.5848	0.005	0	0	0	0.2
3	0.0175	0.435	0	0	0.152	1
4	-1.583	0.068	0	0	0.465	0.5
5	1.5882	0.003	0	0	0.000999	0.39998
6	-1.5795	0.003999	0	0	0.010	0
7	0	0.022	0	-0.022	0.146	0

Result a-2. Robot 's calibrated parameters with two joints 2,3 considered. Average Error = 0.0088035 mm; Maximum Error = 0.019298 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.0175	0.008	0.0175	0.007	0.004	1
2	-1.5848	0.005	0	0	0	0.2
3	0.0175	0.435	0	0	0.152	1
4	-1.583	0.068	0	0	0.465	0.5
5	1.5882	0.003	0	0	0.000999	0.39998
6	-1.5795	0.003999	0	0	0.01	0
7	0	0.022	0	-0.022	0.146	0

Result a-3. Robot 's calibrated parameters with only joints 3, 4 considered. Average Error = 0.032404 mm; Maximum Error = 0.090907 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.017487	0.008001	0.017506	0.007	0.003986	1.001
2	-1.5848	0.004998	0	0	0	0.1996
3	0.017523	0.435	0	0	0.15201	1.0002
4	-1.583	0.068	0	0	0.46499	0.50237
5	1.5881	0.003007	0	0	0.000979	0.3899
6	-1.5794	0.003983	0	0	0.01	0
7	0	0.022002	0	-0.022001	0.14601	0

Result a-4. Robot 's calibrated parameters with only joints 4, 5 considered. Average Error = 0.070256 mm; Maximum Error = 0.17826 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.01748	0.00797	0.01754	0.00699	0.003923	1.0016
2	-1.5848	0.004954	0	0	0	0.19947
3	0.017518	0.43497	0	0	0.15197	0.99679
4	-1.583	0.067946	0	0	0.46496	0.50276
5	-1.5882	0.003004	0	0	0.00106	0.3886
6	-1.58	0.003999	0	0	0.01	0
7	0	0.021996	0	-0.021992	0.14602	0

Result a-5. Robot 's calibrated parameters with only joints 2, 4 considered. Average Error = 0.072118 mm; Maximum Error = 0.17813 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.017698	0.007974	0.017279	0.006971	0.003735	0.9989
2	-1.5847	0.004907	0	0	0	0.20291
3	0.017411	0.43492	0	0	0.15174	0.97635
4	-1.5826	0.067824	0	0	0.46493	0.49184
5	1.5886	0.0029685	0	0	0.001047	0.40808
6	-1.5801	0.0040894	0	0	0.01	0
7	0	0.021991	0	-0.021971	0.14603	0

Result b-1. Robot 's calibrated parameters with only joint 2, joint 3 considered. Average Error = 5.0403e-005 mm; Maximum Error = 0.00013584 mm.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.017692	0.007981	0.017272	0.0069714	0.003724	0.99968
2	-1.5847	0.004908	0	0	0	0.20255
3	0.01743	0.43492	0	0	0.15175	0.97656
4	-1.5826	0.067829	0	0	0.46492	0.49355
5	1.5886	0.002974	0	0	0.001011	0.40187
6	-1.5799	0.004081	0	0	0.01	0
7	0	0.021995	0	-0.021972	0.14603	0

Result b-2. Calibrated parameters with five joints 2, 3,4,5,6 considered. Average Error = 0.0028536 mm; Maximum Error = 0.0049749 mm; K4 = -49.598×10^6 ; K5 = -2769.6×10^6 N/rad.

i	α_{i-1}[rad]	a_{i-1}[m]	β_{i-1}[rad]	b_{i-1}[m]	d_i [m]	θ_i[deg]
1	0.0175	0.008	0.0175	0.007	0.004	1
2	-1.5848	0.005	0	0	0	0.20001
3	0.0175	0.435	0	0	0.152	1
4	-1.583	0.068	0	0	0.465	0.5
5	1.5882	0.003	0	0	0.000999	0.39998
6	-1.5795	0.003999	0	0	0.01	0
7	0	0.022	0	-0.022	0.146	0