State Key Laboratory of Robotics and System

Geometric Parameter Identification of a 6-DOF Space Robot using a Laser-ranger

Yu Liu

Robotic Research Institute of Harbin Institute of Technology

Significance of Parameter Identification

- Repeatability of a robot only represents the ability that the robot follows the same trajectory ;
- Pose accuracy of the robot describes how close the end effector true pose is to desired pose;
- It is necessary to have enough pose accuracy for some orbital maintenance tasks of a space robot, and parameter identification is an important approach to improve the end effector accuracy.
- parameter identification is a software compensation algorithm. It only seeks for the true kinematic parameters and does not physically change the links, joints and controllers of the robot.

Error Sources

- Steady state errors
- Geometrical parameter errors due to machining and manufacturing
- Joint and link flexibility;
- Transmission;
- Temperature; it is a very important factor for a space robot.

So, the space robot calibrated on the ground must be recalibrated on orbit to improve its pose accuracy;

Category

- Geometrical parameter identification;
- Non-geometrical parameter identification.

Research Status

- Research on geometrical parameter identification has been mature;
- Research on non-geometrical parameter identification is till in progress.

Chunhe Gong et al built a comprehensive error model including geometric errors, position–dependent compliance errors and time–variant thermal errors, and robot accuracy was improved by an order of magnitude after calibration.

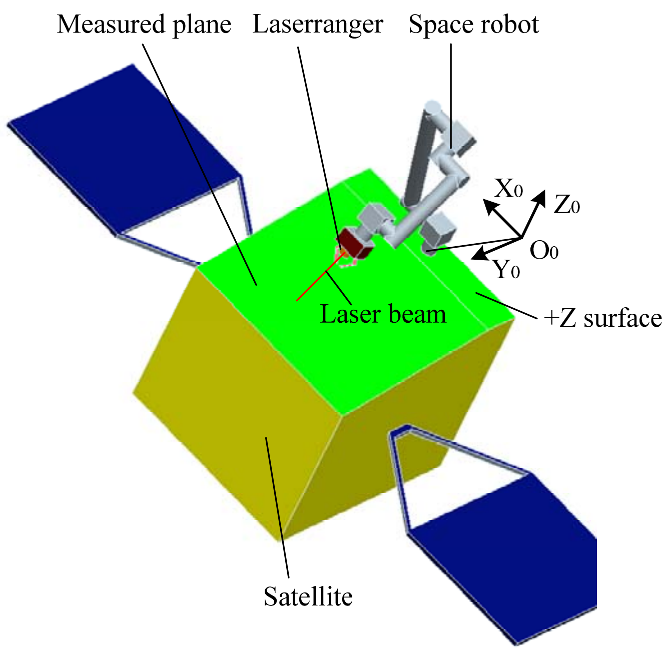
Lightcap et al applied a 30-parameter flexible geometric model to the Mitsubishi PA10-6CE robot, considering the flexibility in the harmonic drive transmission.

Explanation

Space robots are located in micro-gravity environments and move slowly, so non-geometrical errors due to joint and link flexibility will occupy a small proportion, and here they are omitted.

Identification Scheme

- The space robot is fixed on the +Z surface (pointing to the center of the earth) of the satellite, and its end-effector carries a laser-ranger that is used to measure the distance from the starting point of the laser beam to the measured declining plane.
- Some other parameter identification methods using a laser-ranger generally measured the distance from the robot end-point to a known object point, however it was difficult to determine whether the laser beam just passed through the object point in practice.
- Comparatively, The measurement scheme is simple.



$^{i-1}\boldsymbol{A}_i$

Kinematic Model

with the D-H parameter method, the relative translation and rotation from the robot link frame *i*-1 to the frame *i* can be described by a homogeneous transformation matrix $^{i-1}\boldsymbol{A}_i$ as

$$^{i-1}\boldsymbol{A}_i = \begin{bmatrix} C\theta_i & -C\alpha_i S\theta_i & S\alpha_i S\theta_i & a_i C\theta_i \\ S\theta_i & C\alpha_i C\theta_i & -S\alpha_i \cos\theta_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Kinematic Model

However, when a small angle variation creates between two consecutive parallel axes or near parallel axes, with the D-H method it will lead to a large variation of the parameter d_i, Therefore, an extra parameter β_i called the link twist angle is introduced to solve the problem. Post-multiplied the matrix ${}^{i-1}\boldsymbol{A}_i$ by an additional rotation matrix, it can be changed as

$$
{}^{i-1}\boldsymbol{A}_i \leftarrow {}^{i-1}\boldsymbol{A}_i \cdot \mathrm{Rot}\left(y, \beta_i\right) =
\begin{pmatrix}
C\theta_i C\beta_i - S\theta_i S\alpha_i S\beta_i & -S\theta_i C\alpha_i & C\theta_i S\beta_i + S\theta_i S\alpha_i S\beta_i & a_i C\theta_i \\
S\theta_i C\beta_i + C\theta_i S\alpha_i S\beta_i & C\theta_i C\alpha_i & S\theta_i S\beta_i - C\theta_i S\alpha_i C\beta_i & a_i S\theta_i \\
-C\alpha_i S\beta_i & S\alpha_i & C\alpha_i C\beta_i & d_i \\
0 & 0 & 0 & 1
\end{pmatrix}
$$

Kinematic Model

The transformation matrix from the base coordinate frame to the tool frame can be obtained from the well known loop closure equation :

$$\boldsymbol{T}_N = {}^0\boldsymbol{A}_n = {}^0\boldsymbol{A}_1\,{}^1\boldsymbol{A}_2 \cdots {}^5\boldsymbol{A}_6$$

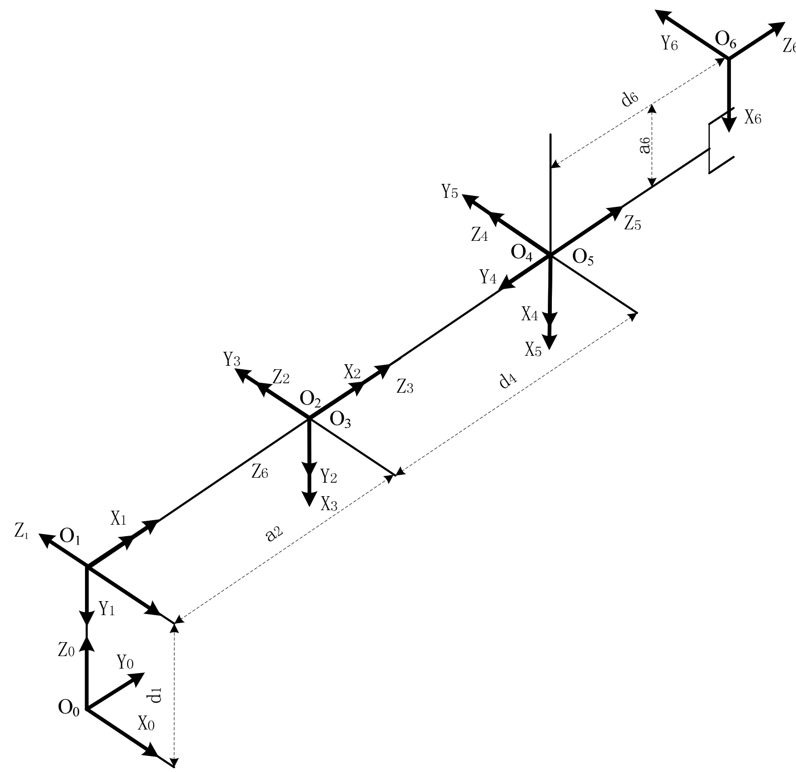
Further the matrix $\boldsymbol{T}_N$ can be divided into the following sub-matrix:

$$\boldsymbol{T}_N = \begin{pmatrix} \boldsymbol{R}_N & \boldsymbol{p}_N \\ 0 & 1 \end{pmatrix}$$

$O_6 - X_6Y_6Z_6$

Configuration of the space robot

The tool frame of the space robot can be chosen arbitrarily. Here, we choose the laser-ranger coordinate frame $O_6 - X_6Y_6Z_6$ fixed to the end-effector as the tool frame. the starting point of the laser beam is located in the origin O_6 the positive direction of the z_6 axis acts as the emission direction of the laser beam.



Independent Parameters

L. Everett gave the following calculative formula of Independent Parameters:

$$C = 4R + 2P + 6$$

The space robot should have 30 independent geometric parameters. However, different from a laser tracker that can measure a six-dimensional pose of the robot, the laser-ranger can only measure the distance. which means that the end effector will lose five constraints. So, in comparison with the laser tracker, using the laser-ranger there are maximally 25 identifiable parameters for the space robot.

Identification Equation

The laser beam unit vector $\boldsymbol{b}_l$ with respect to the base coordinate frame is expressed as

$$\boldsymbol{b}_l = \boldsymbol{R}_N \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

It is assumed that the measured plane equation in the base coordinate frame is

$$\boldsymbol{n}_l \cdot \boldsymbol{p} + f = 0$$

$\boldsymbol{n}_l(n_{lx}, n_{ly}, n_{lz})$ is the unit normal vector of the measured plane.

$\boldsymbol{p}_j = \boldsymbol{p}_s + h\boldsymbol{b}_l$

Identification Equation

Supposed that the laser beam vector $\boldsymbol{b}_l$ intersects the measured plane at the point $\boldsymbol{p}_j$, then according to the relation of the vectors, $\boldsymbol{p}_j$ can be written as

$$\boldsymbol{p}_j = \boldsymbol{p}_s + h\boldsymbol{b}_l$$

$\boldsymbol{p}_s$ is the starting point of the laser beam. h denotes the distance from $\boldsymbol{p}_s$ to the intersectant point $\boldsymbol{p}_j$. Combining the above two equation, we can obtain the following equation:

$$h = -\frac{\boldsymbol{n}_l \cdot \boldsymbol{p}_s + f}{\boldsymbol{n}_l \cdot \boldsymbol{b}_l}$$

Identification Equation

It is known to all that the number of the identification equation is generally greater than that of the identified geometric parameters. Simply, the more identification configurations are chosen to obtain the more identification equations. Through combining these equations the following formula can be given:

d_1

$$\Delta \boldsymbol{h} = \boldsymbol{G} \Delta \boldsymbol{e}$$

$$\Delta \boldsymbol{h} = \begin{bmatrix} \Delta h_1 & \Delta h_2 & \cdots & \Delta h_m \end{bmatrix}$$

$$\Delta \boldsymbol{e} = \left[\Delta \theta_1, \Delta d_1, \Delta a_1, \Delta \alpha_1, \Delta \beta_1, \cdots, \Delta n_{ly}, \Delta n_{lz} \right]$$

$\boldsymbol{G}$ is the identification Jacobian matrix.

Optimal Experimental Design

Since E-optimality is the best criterion to minimize the uncertainty of the end-effector pose of a robot and the variance of the parameters, it is used as the observability index of the optimal experimental design. Its objective function is to maximize the minimum singular value of the identification Jacobian matrix, and it can be written as

$$O_3 = \max \sigma_{\min}(G)$$

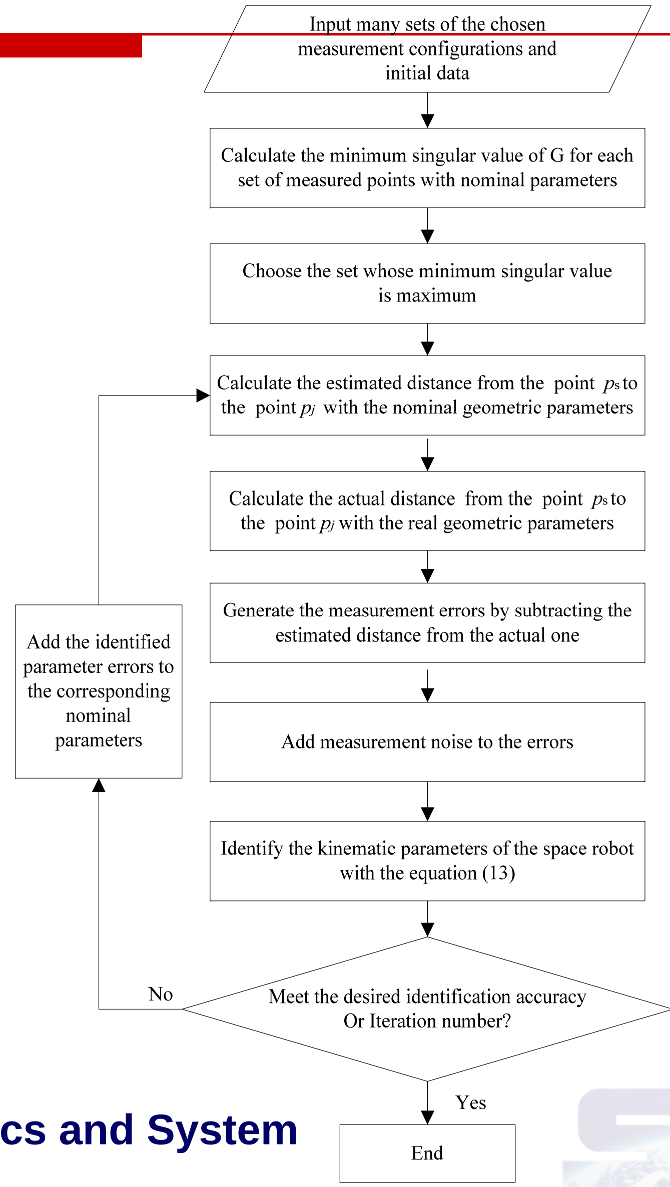
Generally, there are many sets of measurement configurations to be chosen, the set whose minimum singular value is maximal is the optimal experimental design.

Measurement Noise

There are usually some errors in the distance values measured by the laser-ranger. To simulate the real case, measurement noise should be added to the error model so as to calibrate the space robot more exactly. Here, it is assumed that distance measurement noise follows a normal distribution with zero mean and standard deviation 0.2mm.

For the same configuration the more distance measurements will be taken to reduce disturbance of the stochastic measurement noise, then the average of these measurements are provided as the measurand.

Flowchart of Parameter Identification



Initial Condition

Nominal D-H parameters of the space robot

Link No.	θ_n /rad	α_n /rad	a_n /m	d_n /m	$\Delta\beta_n$ /rad
1	$\pi/2$	$-\pi/2$	0	0.5	—
2	0	0	1	—	0
3	$-\pi/2$	$\pi/2$	0	0	—
4	0	$-\pi/2$	0	-0.8	—
5	π	$\pi/2$	0	0	—
6	0	0	-0.12	0.4	0

Pre-assumed geometrical Parameter Errors

Link No.	$\Delta\theta_n$ / mrad	$\Delta\alpha_n$ / mrad	Δa_n / mm	Δd_n / mm	$\Delta\beta_n$ / mrad
1	-7.23	-3.22	0.23	0.73	—
2	0.52	0.13	1.94	—	1.45
3	0.56	-2.23	0.11	0.34	—
4	0.36	1.92	0.18	1.35	—
5	-5.52	-4.83	0.27	0.29	—
6	-0.34	0.62	0.47	0.85	-3.36

Initial Condition

The measured plane equation is chosen as

$$y + 4.6z - 0.69 = 0$$

The equation can not be given such the form as $z + f = 0$, or it will make three geometric parameters of the space robot unidentifiable, i.e. θ_1 , a_1 , d_3 . Obviously, if the measured plane is perpendicular to the axis , the three parameters will make no difference to the measured distance, which will weaken completeness of the identified geometric model.

Measurement Noise

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For the same configuration the more distance measurements will be taken to reduce disturbance of the stochastic measurement noise, then the average of these measurements are provided as the measurand.

Measurement Configuration

101 measurement configurations are chosen in all where the space robot is non-singular.

The two cases will be simulated, namely 50 configurations 10 repetitions (the first case) and 100 configurations 10 repetitions (the second case), x repetitions denote the number of repeated measurements for a same measurement configuration.

According to the optimal experimental design criterion choosing 100 configurations from 101 configurations will calculate 101 minimum singular values , similarly choosing 50 points needs to calculate C_{101}^{50} ones, which are a huge number, and the task is difficult to come true.

We calculate a part of the minimum singular values for the first case and all of them for the second case in simulation.

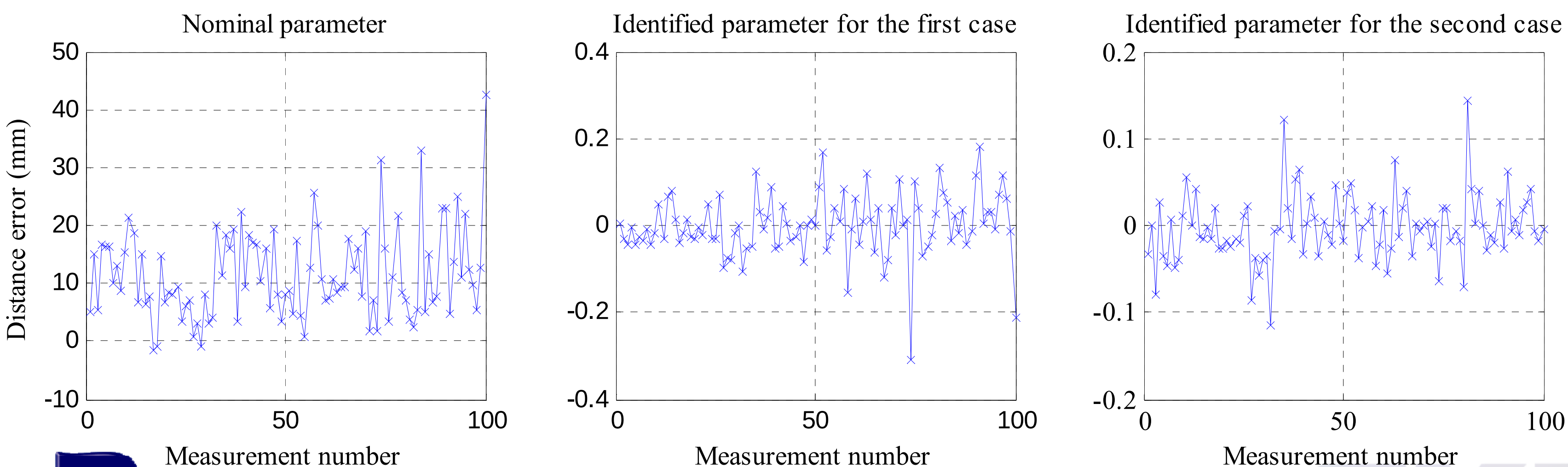
Validation Configuration

Besides, a set of independent validation configurations (20 configurations) distributing in the whole workspace of the space robot are selected to evaluate the identification effect. In nature parameter identification is a fit for the measured data in the measurement configurations, so the extra validation configurations are necessary.

Simulation Result

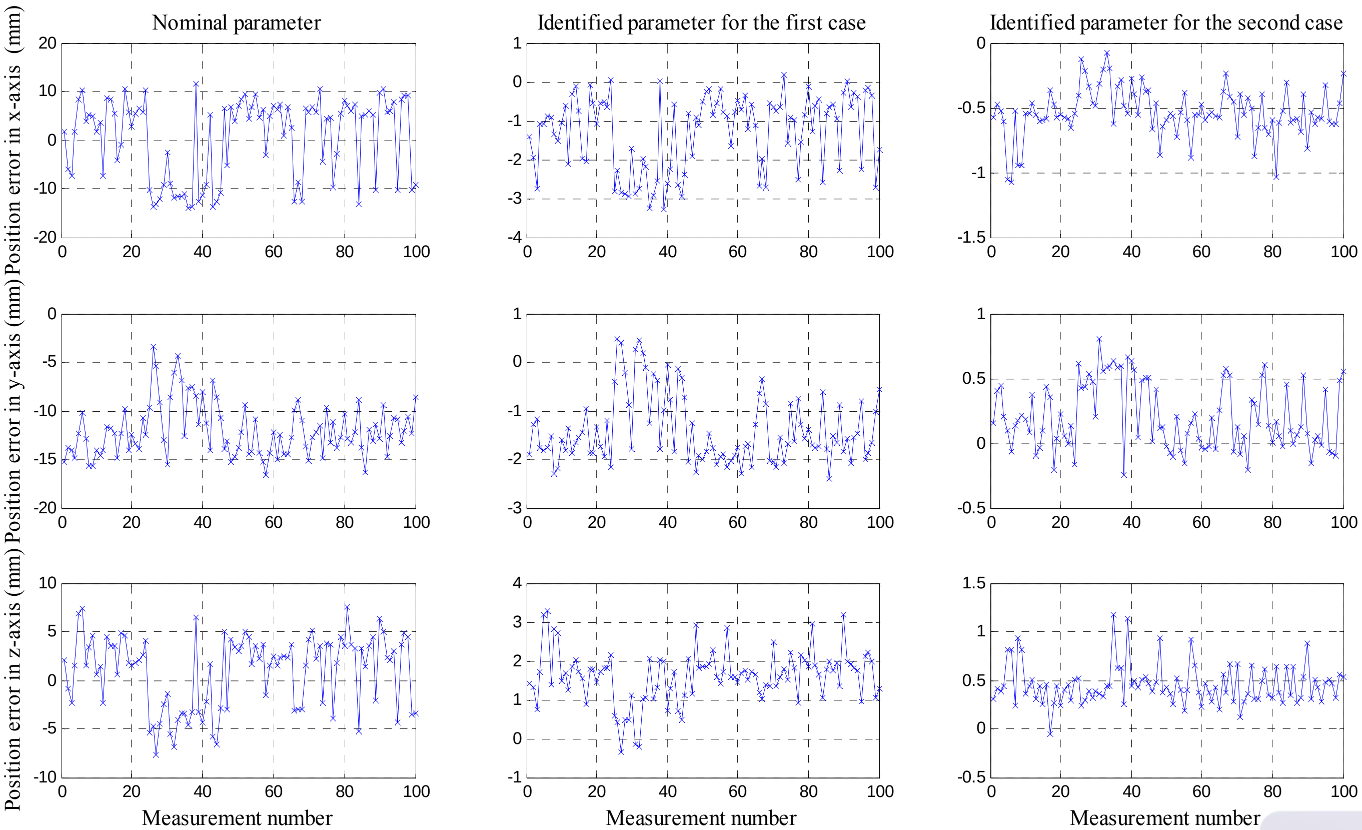
The figure represents the distance errors in the measurement configurations respectively with the nominal parameters, the identified parameters for the first and second cases.

Compared with that prior to identification, after parameter identification the maximum distance error in the measurement configurations decreases significantly, so the parameter identification is a very good fit for the distance measurement values.



Simulation Result

The position errors in the measurement configurations with the nominal, and the identified parameters for the first and second cases are respectively depicted in the figure.



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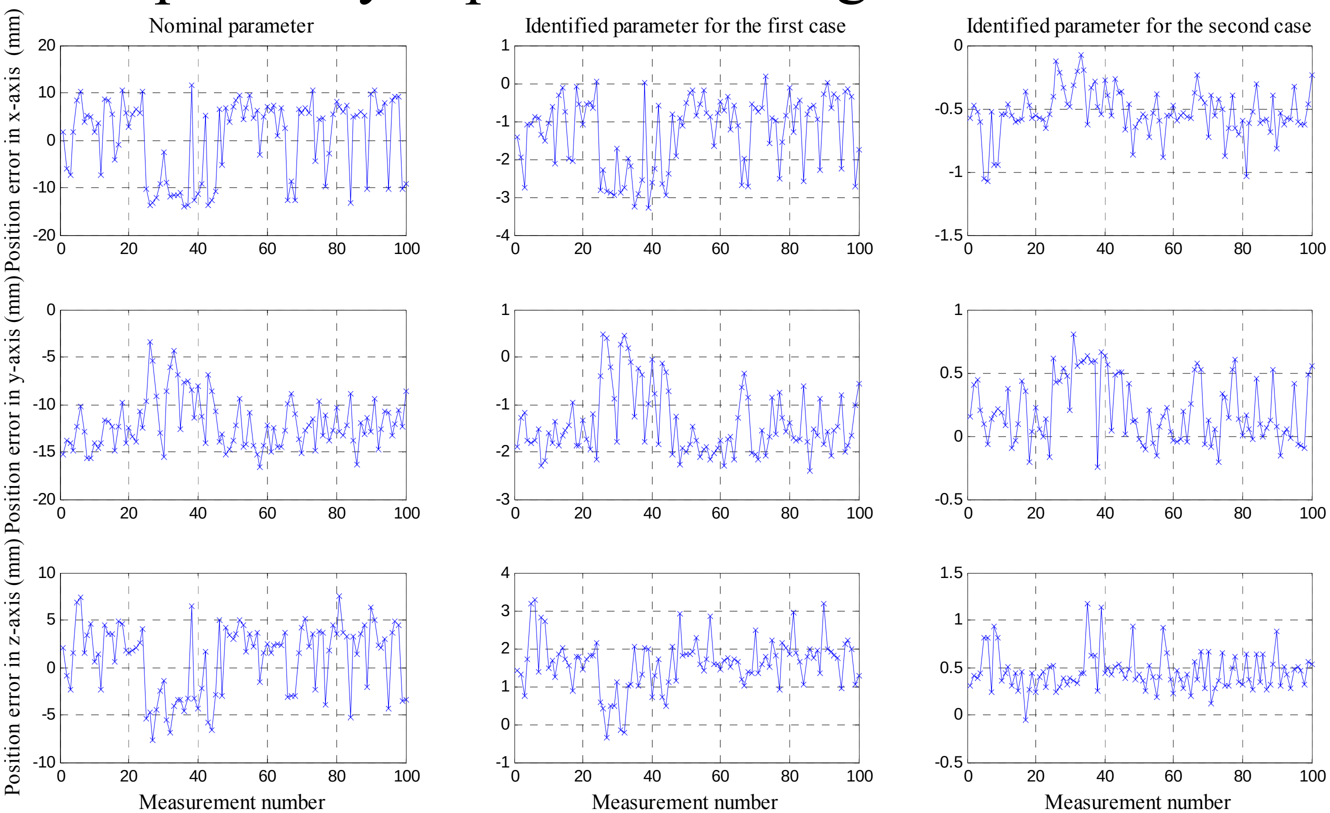
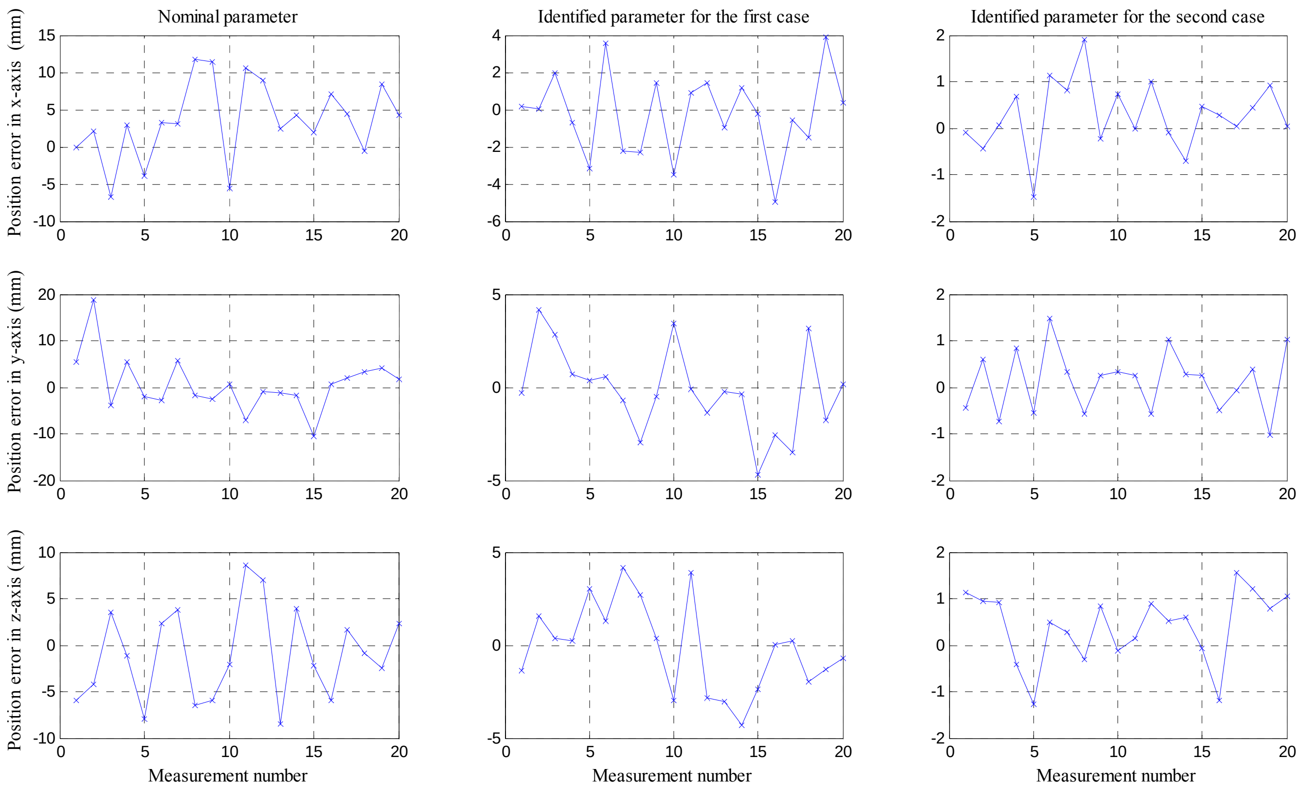
Simulation Result

The orientation errors in the measurement configurations with the nominal, and the identified parameters for the first and second cases are respectively depicted in the figure.



Simulation Result

The position errors in the 20 validaton configurations with the nominal, and the identified parameters for the first and second cases are respectively depicted in the figure.



Simulation Result

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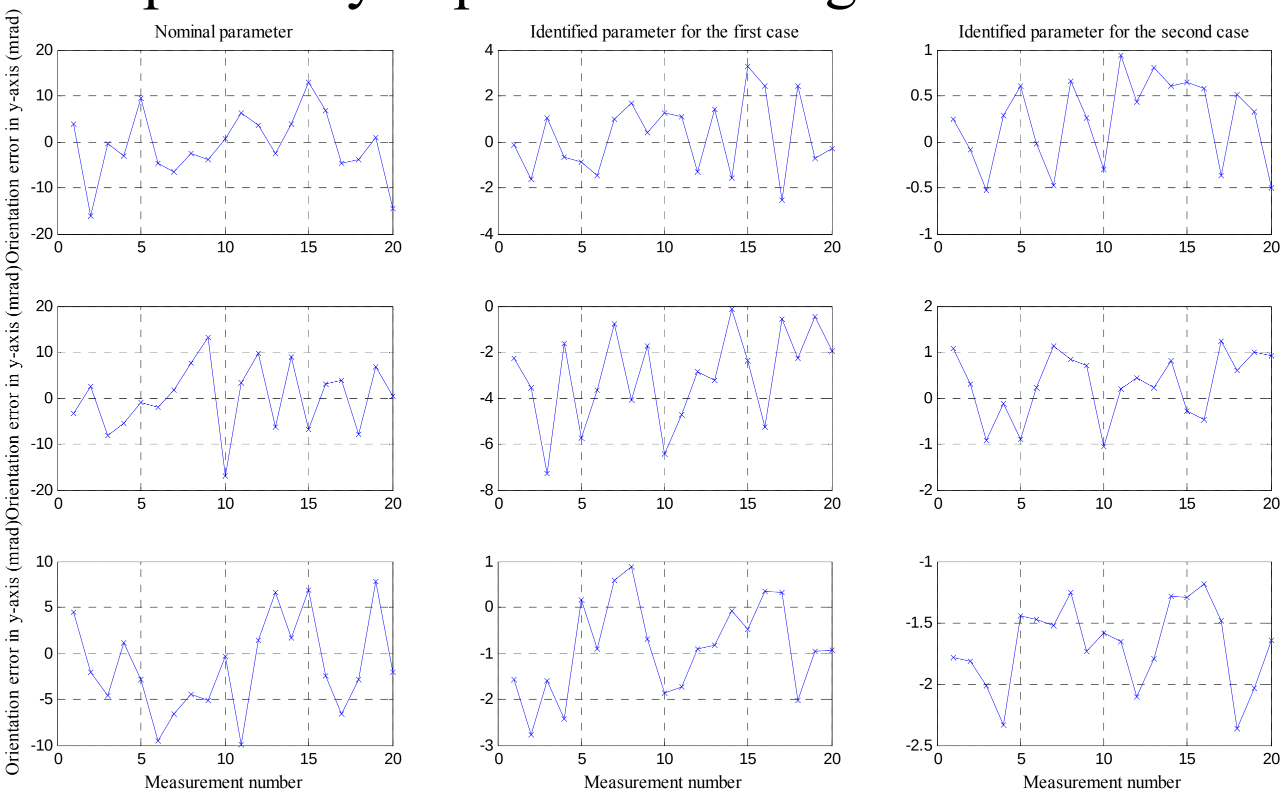

Simulation Result

The following two tables are the identified geometrical parameters.

Link No	$\Delta\theta_n$ / mrad	$\Delta\alpha_n$ / mrad	Δa_n / mm	Δd_n / mm	$\Delta\beta_n$ / mrad
1	-7.8525	-2.4425	-2.1491	0.5724	—
2	1.2119	0.0553	1.6291	—	1.1436
3	0.0949	-1.5013	1.3863	0.2838	—
4	0.2936	2.6439	0.3531	1.2179	—
5	-5.2130	-3.8485	-0.0797	0.2895	—
6	0.5628	0.5207	0.8714	0.7422	-3.7951

Link No	$\Delta\theta_n$ / mrad	$\Delta\alpha_n$ / mrad	Δa_n / mm	Δd_n / mm	$\Delta\beta_n$ / mrad
1	-7.0607	-2.8193	-0.1191	0.1555	—
2	0.8234	0.2574	1.6439	—	1.4527
3	0.3428	-2.0967	1.0172	-0.5597	—
4	0.5364	2.2958	0.0014	1.4096	—
5	-5.6786	-4.2081	0.3607	0.6214	—
6	1.4004	0.4974	0.4545	0.4274	-3.3556

Simulation Result

Comparison of position and orientation errors in the validation configuration is listed in the following table. Comparatively, the identification results for the second case are better than those for the first case as a whole, which shows that increment of the redundant measurement configurations can weaken disadvantageous influence of measurement noise and enhance identification effect.

Error item		RMS position error /mm	RMS orientation error /mrad	Maximum position error /mm	Maximum orientation error /mrad
Nominal parameter	x	2.7612	3.1491	11.7347	16.1688
	y	2.5917	3.2196	18.6857	17.0006
	z	2.2119	2.3480	8.5899	9.9512
Identified parameter for the first case	x	0.9921	0.7003	4.9654	3.2981
	y	1.0148	1.6199	4.6951	7.3035
	z	1.0524	0.5910	4.3151	2.7741
Identified parameter for the second case	x	0.3427	0.2273	1.9067	0.9378
	y	0.2974	0.3374	1.4779	1.2271
	z	0.3785	0.7671	1.5664	2.3669

Summary

With the laser-ranger carried by the end effector a geometric parameter identification method is presented, and the 25 independent parameters of the space robot are identified through simulation. It is simple and convient.

In the process of identification, independence of the parameters is discussed to avoid parameter dependence.

The observability index is used to evaluate the combinations of the measurement configurations, which reduces the possibility of inferior configurations to be introduced.

Measurement noise of the laser-ranger is simulated to meet the actual state as much as possible.

The simulation results show that in spite of distance measurement alone, the identification technique significantly improves pose accuracy of the space robot. which verifies the feasibility of the method.

Thank You.