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Accuracy Analysis for Robotized Assembly System

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***Abstract*—Robotized assembly with high precision is increasingly required in critical applications for high-end products. Considering the complexity of a robotized assembly system, a systematic analysis of the error chain is important to assess the success of an assembly case and to propose a proper assembly strategy. In this paper, a robotized assembly system is studied by defining the key problems, identifying the key consisting, and addressing the key procedures. In particular, this paper proposes an assembly accuracy analysis model for analyzing the error chain of misalignment, which provides a system level assembly accuracy estimation and strategy planning. A practical case is studied with the proposed accuracy analysis method, which is further verified via assembly experiments.**

Keywords—robotized assembly; accuracy analysis; error modeling; misalignment; assembly process; small part assembly

I. INTRODUCTION

With the trend of intelligent manufactory in the new industry revolution [1], industrial robots have been used in more and more segments. At the same time, robotized assembly with high precision is increasingly required in critical applications. Small part assembly, particularly for high-end products in 3C industry [2], is challengeable with strict assembly accuracy, complex assembly system consisting and difficult processes.

In order to assess the success of a robotized assembly case and to design a proper assembly strategy, it is important to have a systematic analysis of the error chain in the robotized assembly system. In past decades, various approaches have been proposed for assembly accuracy analysis and modeling [3-7]. Li et al. [3] and Yang et al. [4] presented the tolerance analysis methods of mechanical assemblies based on deviation propagation, which can help the designers to analyze the tolerances for a success assembly during the design phase. Khodaygan and Movahhedy [5] presented a tolerance analysis of assemblies with asymmetric tolerances based on fuzzy logic, which is capable of modeling uncertainty in dimension sizes with any statistical distribution. Cai [6] presented a tolerance modeling and analysis methodology through a two-step linearization with applications in automotive body assembly, which shows significant computational efficiency. Mao et al. [7] presented mechanical assembly quality prediction method based on state space model, which can predict the influence law of machine precision. Liu [8] presented deviation propagation model in part mating, which can provide an efficient method for predicting and optimizing design assembly precise.

The prior approaches built up the fundament to analysis the assembly problem mathematically. However, none of them considered the complete engineering cycle of robotized assembly. The relationship of the error sources under different assembly system and assembly strategy was not addressed. Therefore, there is still a gap to implement the theoretical analysis on practical assembly.

In this paper, a robotized assembly system is studied by defining the key problems, identifying the key consistencies, and addressing the key engineering procedures. In particular, an assembly model for worst-case error is proposed for analyzing the error chain of misalignment. A system level assembly accuracy estimation and strategy planning are presented. A practical case is studied with the proposed accuracy analysis method, which is further verified via experiments.

II. ROBOTIZED ASSEMBLY SYSTEM

A. Robotized assembly problems definition

As illustration in Fig. 1, an assembly is to align two parts (Part A, Part B) with a certain geometry feature, and to keep the alignment with a certain fixing process [9-10].

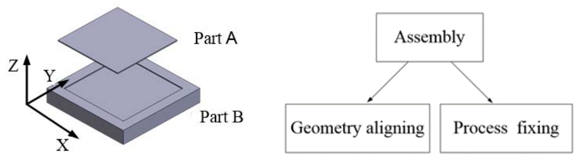


Fig. 1. A scheme of assembly definition.

As illustrated in Fig. 2, a robotized assembly discussed in this paper is defined as:

- Part A is supplied from a feeder, and gripped by robot.
- Part B is transported by a conveyor/turning table/sliding table, and positioned by a fixture.
- The robot grasps part A, and conducts geometry alignment between part A and part B.
- A process to keep the alignment can be concluded by either robot or a special machine.

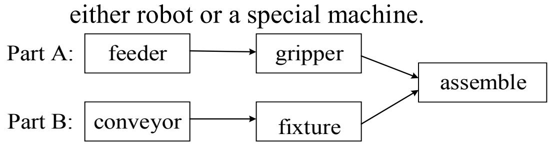


Fig. 2. A scheme of robotized assembly definition.

B. *Consisting of a robotized assembly system*

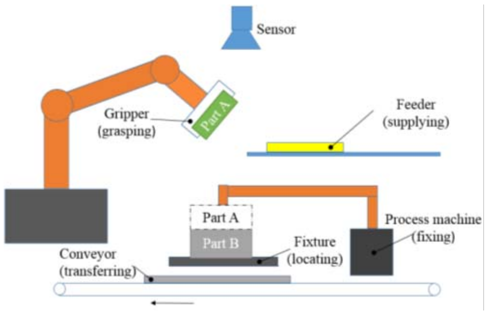


Fig. 3. A robotized assembly system.

As illustrated in Fig. 3, a robotized robot system is composed of industrial robot for manipulating, material handling system for supplying and locating part A, part B, sensors for detecting assembly status, and process machine for fixing.

In particular, material handling system plays an important role in robotized task, such as supplying, locating and transferring. Feeder and fixture can be considered as identical with the same purpose to supply and locate parts.

Typical transferring system includes conveyor, turning table, sliding table. As a moving mechanism, the transfer system introduces position repeatability. By considering the involvement of transferring system, feeding/fixing mode is defined as:

- In station mode: feeder/fixture is fixed in a dedicated location of a robot station.
- Via transfer mode: feeder/fixture is transferred from the transferring system.

As a summary, key characteristics of feeder/fixture are illustrated in Fig. 4.

- Repeatability: it shows how repeatable a feeder/fixture is positioned in the workspace of a robot. It is only counted when transferring system is involved, namely, feeding/fixing is in "From conveyor mode".
- Clearance: it indicates the designed dimension gap between the ideal part and ideal pocket in a feeder/fixture.
- Deviation: machining error causes the geometry deviations (i.e. dimension and position) of a feeder/fixture [11].

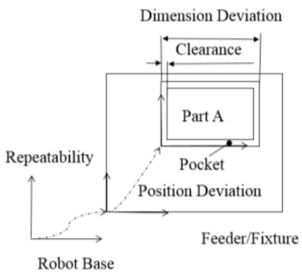


Fig. 4. The key characteristics of feeder/fixture.

Typical grasping system includes finger gripper and vacuum gripper. As illustrated in Fig. 5, repositioning repeatability of part A w.r.t. (with respect to) robot flange coordinate is the key characteristic of grasping system. In particular, gripper with single finger has zero repeatability. Vacuum gripper does not reposition part A, where the repeatability is not applicable and the grasped part position w.r.t. robot flange is depending on the feeder.

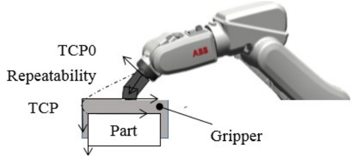


Fig. 5. A key characteristics of grasping system.

In summary, the key consistency of a robotized assembly system is outlined with key characteristics and responding denotations as in TABLE I.

TABLE I A summary of consistency of a robotized assembly system

Consistency		Key Characteristic	Denotation
Industrial Robot		Repeatability	e^{robot}_{rep}
		Absolute Accuracy	e^{robot}_{acc}
Material Handling System	Transfer system	Repeatability	$e^{transfer}_{rep}$
	Feeder/Fixture	Clearance	$e^{feeder/fixture}_{clc}$
		Deviation	$e^{feeder/fixture}_{dev}$
	Grasping system	Repeatability	$e^{gripper}_{rep}$
Sensor		Resolution	e^{sensor}_{res}
		Repeatability	e^{sensor}_{rep}
		Accuracy	e^{sensor}_{acc}

III. Robotized Assembly Accuracy Analysis

A. *Misalignment analysis*

The difficulty of assembly is the misalignment caused by deviations from each consisting of a robotized assembly system. As illustrated in Fig. 6, assuming ideal alignment can be achieved with absolute coincidence of the target geometry feature in part A and part B.

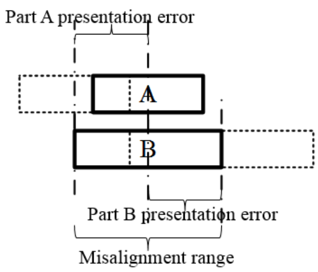


Fig. 6. A scheme of misalignment.

In future assembly, part A and part B will not present at the same position as in ideal alignment. This difference is defined as presentation error of part A and part B. Therefore, the worst misalignment can be formulated as the sum of part A presentation error and part B presentation error.

In particular, part presentation error is caused by repeatability of actuators, clearance of material supply mechanism and deviation of mechanical part. Detailed error sources of part presentation error are listed in TABLE II.

TABLE II Error sources of part presentation error

Source	Part A presentation error	Part B presentation error
Repeatability (e_{rep})	Robot, Gripper	Transfer system
Clearance (e_{clc})	Feeder	Fixture
Deviation (e_{dev})	Feeder, part A	Fixture, part B

It is worth noting that sensor-based control is the premium way to mitigate the misalignment, but it can increase the cost and reduce the cycle time for robotized assembly. The value of an assembly accuracy analysis is to figure out a proper assembly strategy for a target assembly goal, which should not introduce overqualified equipment.

B. *The proposed assembly accuracy model*

An assembly accuracy model is illustrated in Fig. 7, where the accuracy is expressed as a region to a center that indicates the ideal alignment. The assembly accuracy is the accumulation of golden alignment, misalignment, and process loss. In particular, golden alignment and misalignment lead to geometry alignment accuracy. A successful assembly means the region of assembly accuracy is smaller than the region of assembly tolerance.

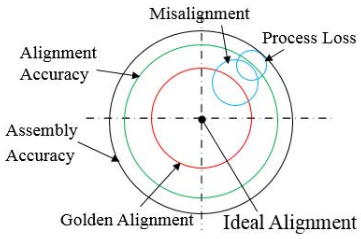


Fig. 7. Assembly accuracy model based on golden alignment.

For further analyzing, the assembly accuracy is formulated as:

$$e_{ass} = e_{ali} + e_{los} \quad (1)$$

$$e_{ali} = e_{gld} + e_{mis} \quad (2)$$

Where, e_{ass} indicates assembly accuracy; e_{ali} indicates alignment accuracy; e_{los} indicates process loss; e_{gld} indicates teach accuracy; e_{mis} indicates misalignment error. In particular, e_{gld} depends on robot programming accuracy with golden alignment, while e_{los} depends on detailed fixing process.

The misalignment can be expressed as:

$$e_{mis} = e_{pre}^{A} + e_{pre}^{B}$$
$$= (e_{rep}^{A} + e_{dev}^{A} + e_{clc}^{A}) + (e_{rep}^{B} + e_{dev}^{B} + e_{clc}^{B}) \quad (3)$$

Where, $e_{rep}^{A}, e_{dev}^{A}, e_{clc}^{A}$ indicate repeatability, deviation, and clearance of part A respectively; $e_{rep}^{B}, e_{dev}^{B}, e_{clc}^{B}$ indicate repeatability, deviation, and clearance of part B respectively. $e_{rep}^{A}, e_{dev}^{A}, e_{clc}^{A}, e_{rep}^{B}, e_{dev}^{B}, e_{clc}^{B}$ can be derived as:

$$e_{rep}^{A} = k_{rep}^{robot} \times e_{rep}^{robot} + k_{rep}^{gripper} \times e_{rep}^{gripper} \quad (4)$$

$$e_{dev}^{A} = k_{dev}^{partA} \times e_{dev}^{partA} + k_{dev}^{feeder} \times e_{dev}^{feeder} \quad (5)$$

$$e_{clc}^{A} = k_{clc}^{feeder} \times e_{clc}^{feeder} \quad (6)$$

$$e_{rep}^{B} = k_{rep}^{transfer} \times e_{rep}^{transfer} \quad (7)$$

$$e_{dev}^{B} = k_{dev}^{partB} \times e_{dev}^{partB} + k_{dev}^{fixture} \times e_{dev}^{fixture} \quad (8)$$

$$e_{clc}^{B} = k_{clc}^{fixture} \times e_{clc}^{fixture} \quad (9)$$

The detailed error value of repeatability (e_{rep}^{robot}, $e_{rep}^{gripper}$, $e_{rep}^{transfer}$) can be obtained by the product datasheet or identified via experiments; deviation (e_{dev}^{partA}, e_{dev}^{feeder}, $e_{dev}^{fixture}$, e_{dev}^{partB}) depends on the required the machining accuracy; clearances (e_{clc}^{feeder}, $e_{clc}^{fixture}$) are determined by the design of material handling system.

In particular, k_{x}^{y} are binary parameters to decide whether relevant errors are counted or not for error calculation in (7)-(9). They are the most critical parameters to be identified in the proposed assembly accuracy model.

Considering the complex consistence and procedure of a robotized assembly system as discussed in Section 2, k_{x}^{y} can be affected by various conditions as summarized in TABLE III. In particular, "Sensor Compensation" misalignment control mode means measuring the error by once, while "Sensor Guiding" means measuring the error by multiple times until the error coverages.

TABLE III Condition definitions in a robotized assembly

Assembly Condition Definition	**Conditions**
Gripper type $C^{gripper}$	• "Single Finger" • "Double Finger" • "Vacuum"
Feeder/fixture type C^{feeder} or $C^{fixture}$	• "Tray" • "Repositioning Mechanism"
Feeding/fixing mode $C^{feeding}$ or C^{fixing}	• "In Station" • "Via Transfer"
Misalignment control mode $C^{MisCtrl}$	• "Mechanical" • "Sensor Compensation" • "Sensor Guiding"

Therefore, the binary value of k_x^y can be determined by considering combinations of the assembly condition as listed in TABLE IV.

TABLE IV k_x^y value determination under assembly condition combination

k_x^y	Binary Value	
	0	1
k_{rep}^{robot}	$C^{MisCtrl}$="Sensor Guiding"	Otherwise
$k_{rep}^{gripper}$	Otherwise	$C^{gripper}$ = "Double Finger" AND $C^{MisCtrl}$ = "Mechanical"
k_{dev}^{feeder}	Otherwise	$C^{gripper}$ = "Vacuum" AND $C^{feeding}$ = "Via Transfer" AND $C^{MisCtrl}$ = "Mechanical"
k_{clc}^{feeder}	Otherwise	$C^{gripper}$ = "Vacuum" AND C^{feeder} = "Tray" AND $C^{MisCtrl}$="Mechanical"
k_{dev}^{partA}	$C^{MisCtrl}$="Sensor Compensation" OR $C^{MisCtrl}$="Sensor Guiding"	Otherwise
$k_{rep}^{transfer}$	(C^{fixing}="In Station" AND $C^{MisCtrl}$="Mechanical") OR ($C^{gripper}$="Vacuum" AND $C^{feeding}$="Via Transfer" AND C^{fixing}="Via Transfer" AND $C^{MisCtrl}$="Mechanical" AND "Feeder and fixture are the same one") OR $C^{MisCtrl}$="Sensor Compensation" OR $C^{MisCtrl}$="Sensor Guiding"	otherwise
$k_{dev}^{fixture}$	$C^{MisCtrl}$="Sensor Compensation" OR $C^{MisCtrl}$="Sensor Guiding" OR C^{fixing}="In Station"	Otherwise
$k_{clc}^{fixture}$	Otherwise	$C^{fixture}$="Tray" AND $C^{MisCtrl}$="Mechanical"
k_{dev}^{partB}	$C^{MisCtrl}$="Sensor Compensation" OR $C^{MisCtrl}$="Sensor Guiding"	Otherwise

In general, under "Mechanical" misalignment control, repositioning mechanism in feeder/fixture can be helpful to eliminate the clearances. When repositioning gripper ("Double Finger" or "Single Finger"), feeder deviations can be eliminated as long as part A is within the grasping range.

As illustrated in Fig. 8, a special condition to eliminate transfer system repeatability is to supply part A and part B with the tray as both feeder and fixture, and to grasp part A by vacuum gripper. A vacuum gripper has the feature to maintain the error of part supplier, so it can compensate the error caused by transfer system repeatability which occurs on part B as well.

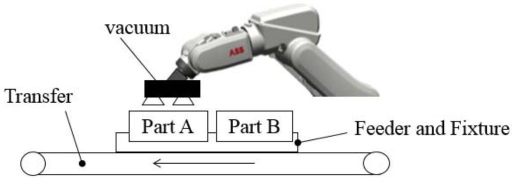


Fig. 8. A special condition to eliminate transfer system repeatability mechanically.

IV. Assembly Case Study

A. Assembly case

In this section, assembly of USB disk is used for a study case. Geometric dimensions and tolerance of USB disk are shown in Fig. 9.

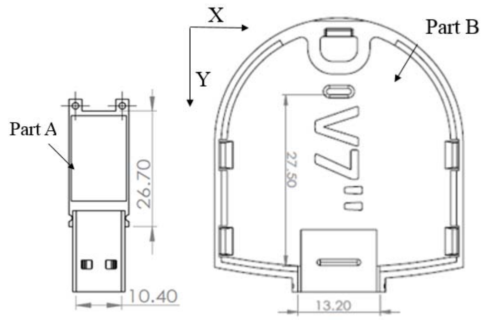


Fig. 9. An assembly case.

In this case, the assembly requirement is that the PCB is put in housing of USB disk based on aligning. According to assembly relation, the different direction assembly requirements accuracy, where the chamfer can be taken into account, are calculated as follow:

The assembly requirement accuracy of X direction is calculated as:

$$e_{req} = \frac{13.2-10.4}{2}\,\text{mm} = 1.4\text{mm} \tag{12}$$

The assembly requirement accuracy of Y direction is calculated as:

$$e_{req} = \frac{27.5-26.7}{2} = 0.4\ \text{mm} \tag{13}$$

B. Assembly strategy plan

An assembly plan includes proposing assembly condition, ensuring value of error and k_x^y. In this paper, the assembly strategy is presented in TABLE V.

TABLE V The assembly strategy

Robot type	Gripper type	Feeder/ fixture	Feeding/ fixing mode	Misalignment Control mode
IRB120, ABB	Double Finger, SMC	Tray, seven level	Via Transfer, Bosch conveyor	Mechanical

According to TABLE IV and TABLE V， the specific error values of error and k_x^y for the study case, are determined in TABLE VI.

TABLE VI The value of error and k_x^y

	Error (mm)		k_x^y	
	X direction	Y direction	X direction	Y direction
e_{rep}^{robot}	0.010	0.010	1	1
$e_{rep}^{transfer}$	0.020	0.020	1	1
e_{clc}^{feeder}	0.075	0.075	0	1
$e_{clc}^{fixture}$	0.100	0.100	1	1
e_{dev}^{feeder}	0.018	0.021	0	1
$e_{dev}^{fixture}$	0.050	0.050	1	1
$e_{rep}^{gripper}$	0.010	0.010	1	1
e_{gld}	0.050	0.050	1	1

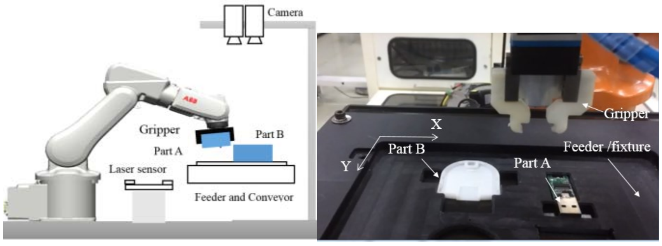
The process loss is 0 in the study case, since the fixing process is clearance fitting. Assembly programming mode selects golden alignment based and teaching mode selects manual teaching. In order to eliminate effect of part deviation for assembly system accuracy analysis, all experiments use same part. The feeder and fixture are same one because part A, B are put same tray as illustrated in Fig. 10. According to TABLE VI and (3)–(9), the e_{mis} can be calculated. Then, the e_{ali}, e_{ass} can be calculated and the result is shown in TABLE VII combing with (1)–(2).

TABLE VII Strategy error analyzed result

	X direction	Y direction
Misalignment accuracy (e_{mis}(mm))	0.190	0.286
Alignment accuracy(e_{ali}(mm))	0.240	0.336
Assembly accuracy(e_{ass}(mm))	0.240	0.336

V. Experimental Result

A. The experimental robot assembly system

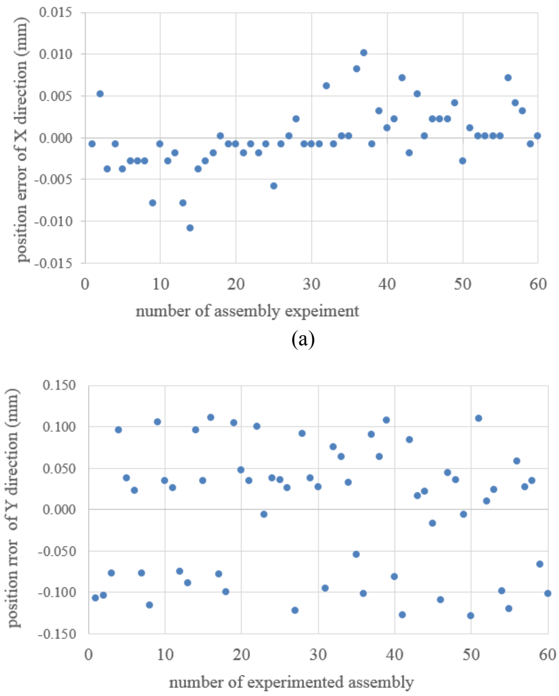


(a) (b)

Fig. 10. The proposed experiment platform: (a) scheme platform; (b) reality platform.

The proposed strategy in section 4 can be implemented in the experiment platform as shown in Fig. 10. The experiment platform consists of ABB IRB120 robot, parts, transfer system, COGNEX company cameras, and Keyence IG-028 laser sensors. The transfer system conveys part A and B together. Position of part A is measured by laser sensor, and position of part B is measured by fixed cameras. Meanwhile, robot implements assembly task.

B. Results of part misalignment



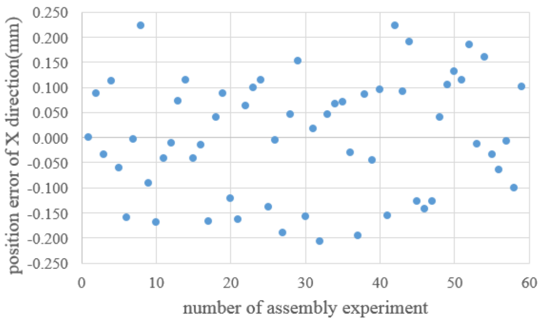
(b)

Fig. 11. Position variation of part A after pickup: (a) Position variation of X direction; (b) Position variation of Y of direction.

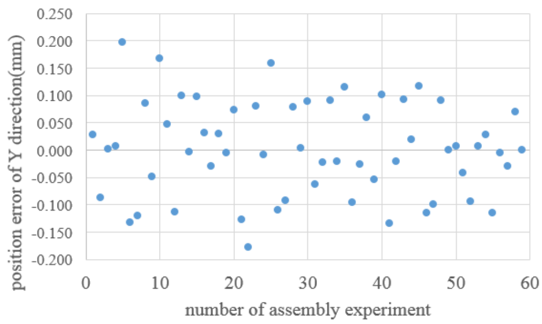
The part A is grasped by robot from conveyor, and putted in the range of laser sensor work to measure position of part A in both X and Y direction. In order to accurately evaluate the misalignment of part A, this experiment is repeated for sixty times.

Fig. 11 shows the position error between the experiment assembly position of part A and golden alignment by manual teaching. The X direction misalignment error is within 0.011mm because of finger gripper, and the Y direction misalignment error is within 0.129mm.

When feeders transfer part B into measured position, two cameras take photos for position feature in opposite angle of part B. The software can give out part B position by fitting position feature every time. In order to accurately evaluate the misalignment, this experiment is repeated for sixty times.



(a)



(b)

Fig. 12. Position variation of part B before placement: (a) Position variation of X direction; (b) Position variation of Y direction.

As shown in Fig. 12, the position error between the experiment assembly position of part B and golden alignment by manual teaching. The position error is within 0.223mm in X direction, and is within 0.197mm in Y direction.

TABLE VIII Required, estimated and actual assembly result

	X direction	Y direction
Required assembly accuracy (e_{req}(mm))	1.400	0.400
Estimated assembly accuracy (e_{ass}(mm))	0.240	0.336
Actual assembly accuracy (e_{act}(mm))	0.234	0.326

In TABLE VIII, comparing estimated assembly accuracy and actual assembly accuracy in X, Y direction, the result can be shown that all actual assembly accuracy is within the range of estimated assembly accuracy. Furthermore, the estimated errors are within 0.01mm in X, Y direction for worst-case. Based on comparing result, we can validate correctness and feasibility of assembly accuracy analysis model. So, it can be applied to estimate robotized assembly system accuracy and to plan assembly strategy.

VI. Conclusions

In this paper, a robotized assembly system is studied by defining the key problems, identifying the key consistencies, and addressing the key engineering procedures. In particular, an assembly model is proposed for analyzing the error chain of misalignment. A system level assembly accuracy estimation and strategy planning are presented. A practical assembly case is studied with the proposed accuracy analysis method, which is further verified via experiments. As shown in experimental results, the estimated worst-case assembly accuracy aligns well with actual assembly accuracy. Thus, the proposed assembly model can be applied to analyze a complexed robotized assembly system and to plan an assembly strategy with reliable worst-case accuracy estimation.

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