PPRIME FORUM

« Mechanical Design and Mechatronics of robotics systems »

Futuroscope, November , 2014

Lecture hall, SP2MI building

rue Gustave Eiffel Futuroscope Chasseneuil, France

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The FORUM organized by the Pprime Institute offers the opportunity to PhD students and researchers from the robotics community to meet experts in order to exchange with them about most recent scientific results. This event provides to participants a space of reflection and privileged exchange.

The FORUM is dedicated to Mechanical Design and Mechatronics of robotics systems. Two themes, in the field of interest of the robotics team of Pprime institute, are considered during this FORUM.

- The design of mechanical hands for dexterous manipulation,
- The design of complex poly-articulated mechanisms (parallel mechanisms).

The forum is organized over three days with a program focused on presentations and panel discussions. In this context, we will have four guest speakers:

- Yukio Takeda, Professor, Tokyo Institute of Technology, Japan
- Philippe Wenger, Directeur de recherches au CNRS, IRCCyN-Nantes, France
- Markus Grebenstein, doctor, DLR German Aerospace Center, Munich, Germany
- Chin-Hsing Kuo, Professor, National Taiwan University of Science and Technology, Taiwan

PPRIME Forum

«Mechanical Design and Mechatronics of robotics systems»

Thursday, November 6: « Kinematic optimization of complex poly-articulated systems »

Morning: 10h-12h

- Yukio Takeda, Professor Tokyo Institute of Technology - Japon
  - Title : « Kinematic Design of Compensatable Parallel Manipulators »
  - Panel discussion

Afternoon: 14h-17h

- Philippe Wenger, Directeur de recherches au CNRS IRCCyN Nantes - France.
  - Title : « Coping with singularities in the design of parallel-manipulators »
  - Panel discussion

program

- Yukio Takeda, Professor Tokyo Institute of Technology – Japon
  - Title : « Kinematic and Dynamic Analysis and Design of 3-RPSR Parallel Mechanism for Pipe-Bender »
  - Panel Discussion

Friday, November 19: « Design of medical robots / Design of mechanical hands »

Morning: 10h-12h

- Chin-Hsing Kuo, Professor National Taiwan University of Science and Technology - Taiwan
  - Title : « Applications of Mechanism Design Theories for Surgical Robotics »
  - Panel Discussion

Afternoon: 14h-17h

- Sebastian Wolf, Doctor, DLR German Aerospace Center, Munich, Germany
  - Title : « Design of the DLR-Hand Arm System - Focus on Variable Impedance Actuation (VIA) »
  - Panel Discussion

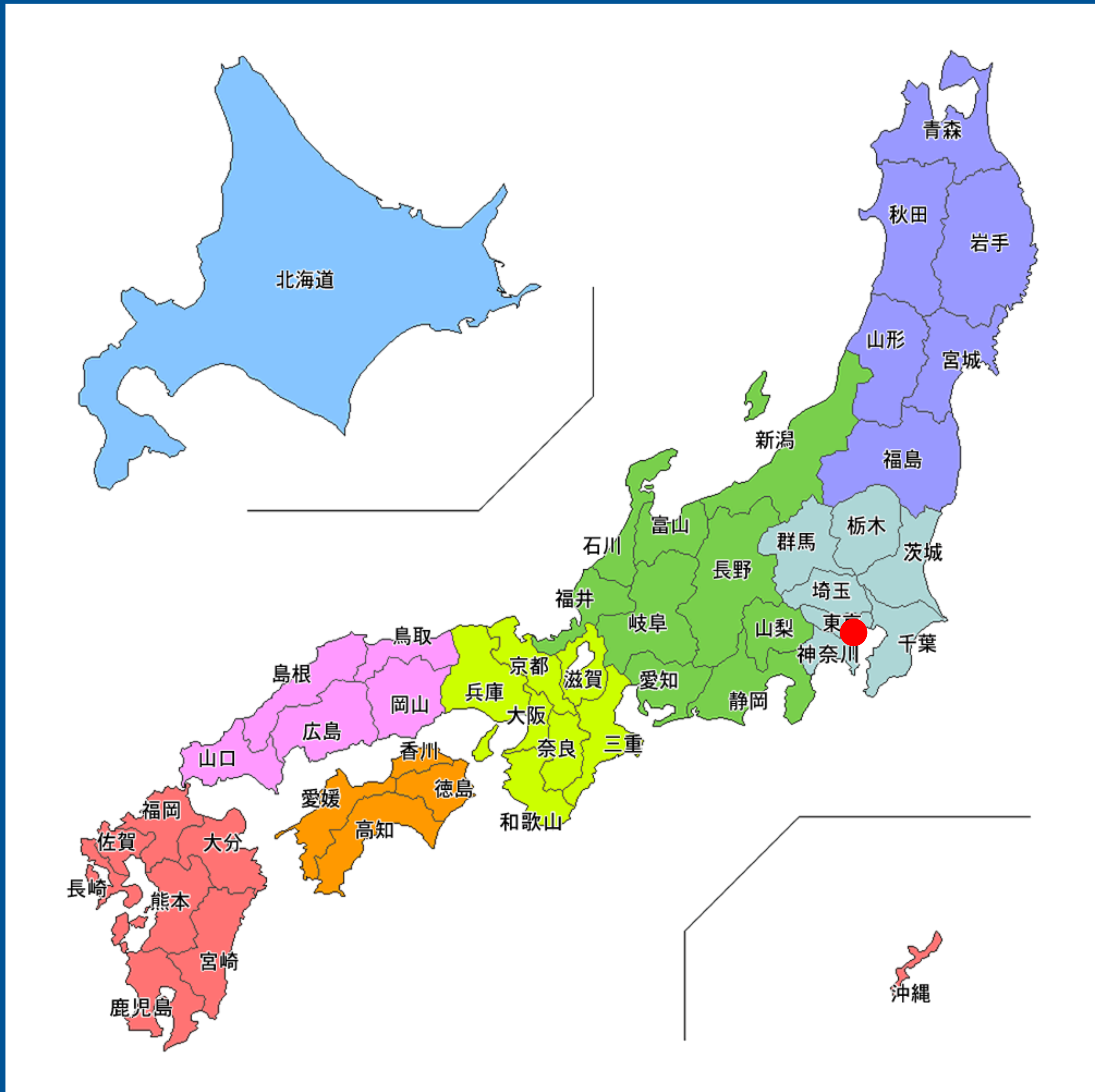
Contents

- Introduction of our Lab. slide
- Introduction of previous researches on parallel mechanisms in our lab. slide
- Main topic: kinematic design of compensatable parallel manipulators

What is Tokyo Tech?

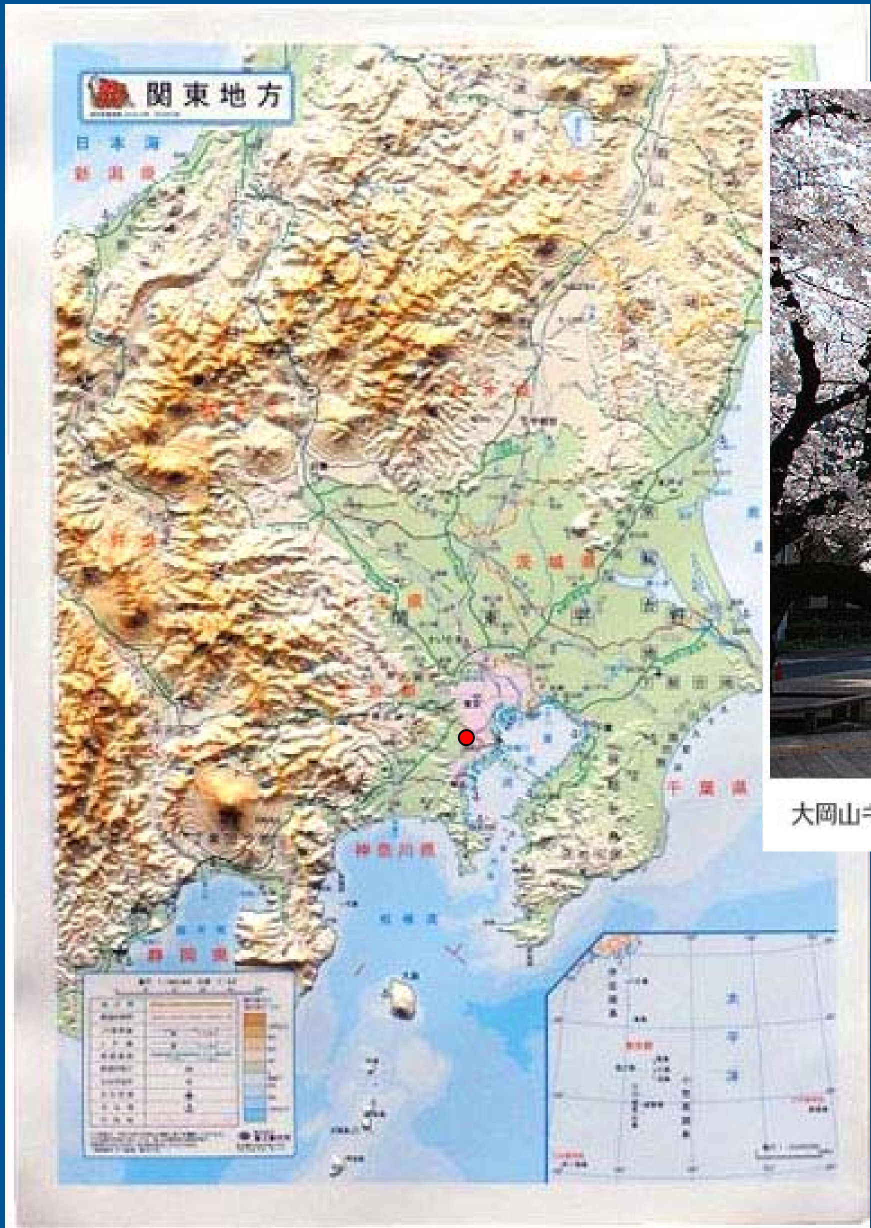
- 3 schools for undergraduates: Science, Engineering, Bioscience and Biotechnology
- 6 graduate schools: Science and Engineering, Bioscience and Biotechnology, Interdisciplinary Science and Engineering, Information Science and Engineering, Decision Science and Technology, Innovation Management
- Number of students：4800 in undergraduate schools(860 in science, 3300 in engineering, 640 in bioscience and biotechnology, 3600 in master course of graduate schools, 1550 in doctoral course of graduate schools, 1320 from foreign countries
- Number of teaching staffs: 1150, number of administration staffs: 1700

Where is Tokyo Tech?



Where is Tokyo Tech?

Tokyo Institute of Technology
Mechanical Systems Design Lab.



大岡山キャンパスの桜

本館と桜。卒業式，入学式の思い出の風景になります。

Cherry blossom and main building (March-April)

Views of Tokyo Tech

Ginko street (November)

Library

Information of our Lab.

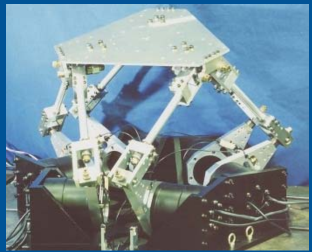
- Department: Mechanical Sciences and Engineering
- Prof. Yukio TAKEDA, Dr. Eng.
- Assist. Prof. Daisuke MATSUURA, Dr. Eng.
- Assist. Prof. Shinji TANAKA, Dr. Eng.
- Graduate Students

  Master course: 4(first year)+4(second year)
- Undergraduate Students: 4
- Exchange/Research Students: 4 (Netherland, Sweden, China)

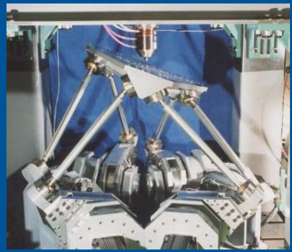
Research Area of our Lab.

- Kinematics (Analysis and Synthesis)
- Mechanisms (Parallel Mechanism, etc.)
- Machine Elements (Joint, Brake, etc.)
- Welfare Machines (Walking Assist, Rehabilitation, etc.)
- Machines (Machine Tools, Pipe Bender)
- Positioning, Measurement

Robot Mechanism (Parallel Mechanisms)

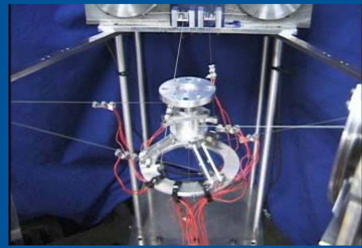



Manipulators

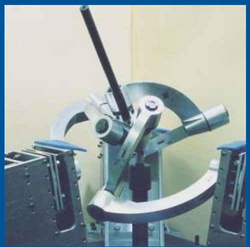


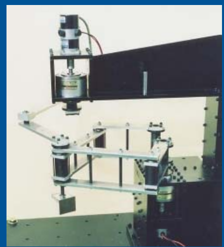
Machine Tool

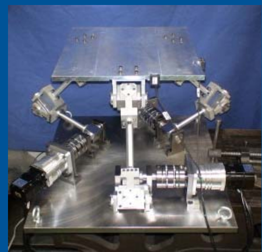

Positioning Manipulator

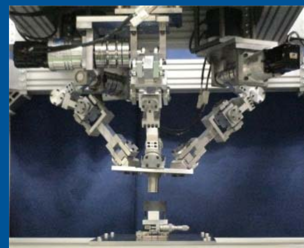


VR

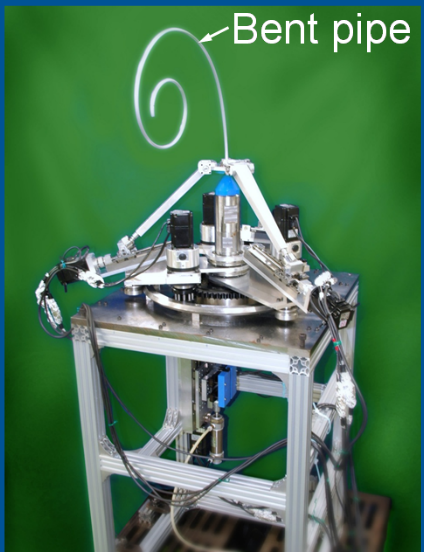




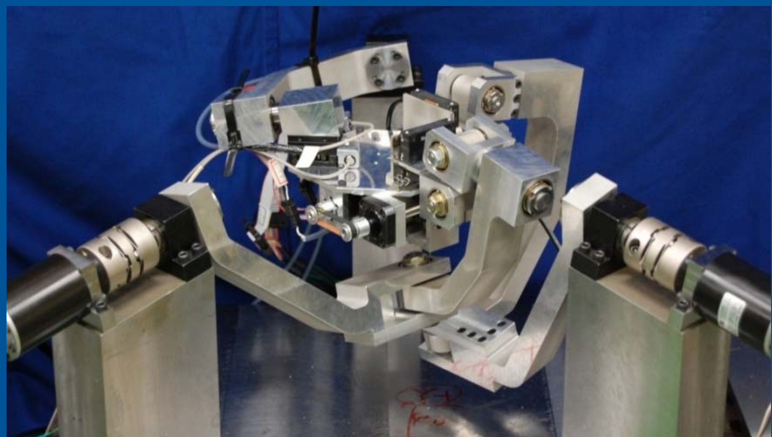




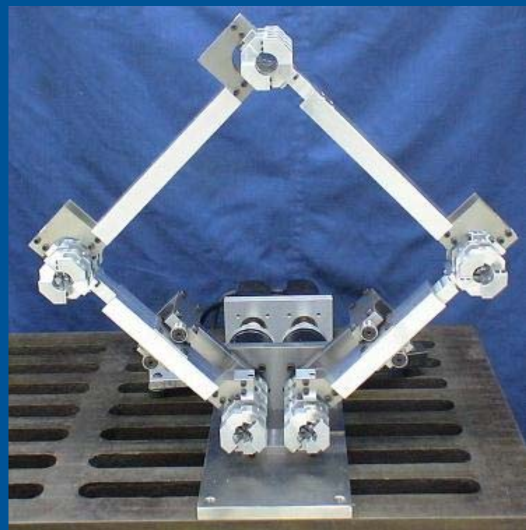
Manipulators



Pipe Bender



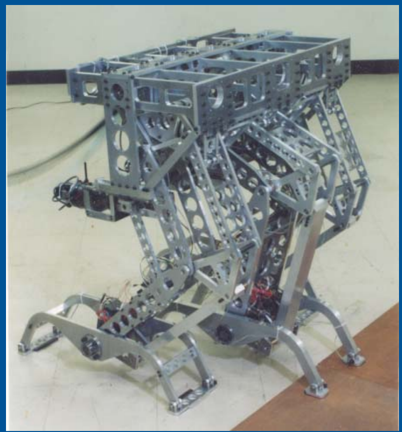
Machine Tool



Manipulator in Vacuum

Walking Assist Machines/Devices

Walking/Running Machines

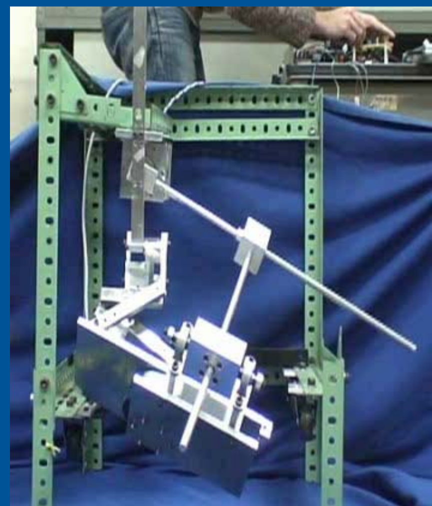



Walking Chair



Walking Assist Machine Using clutches

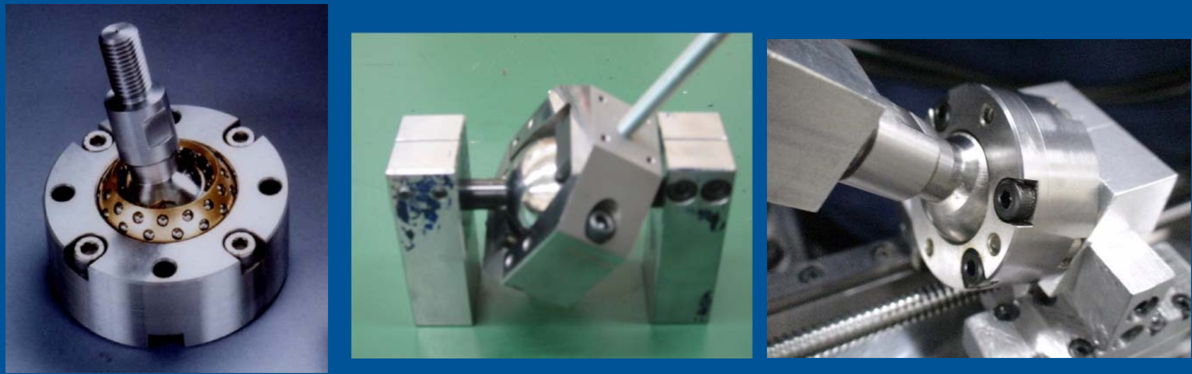

Water Surface Running Machine



Joint Rehabilitation Mechanism

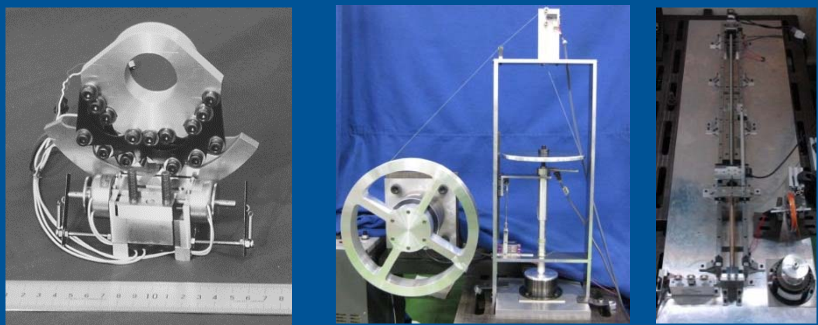
Machine Elements/Manipulators

Tokyo Institute of Technology
Mechanical Systems Design Lab.

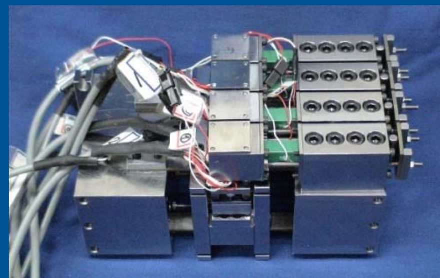


Rolling/Sliding Spherical Joints

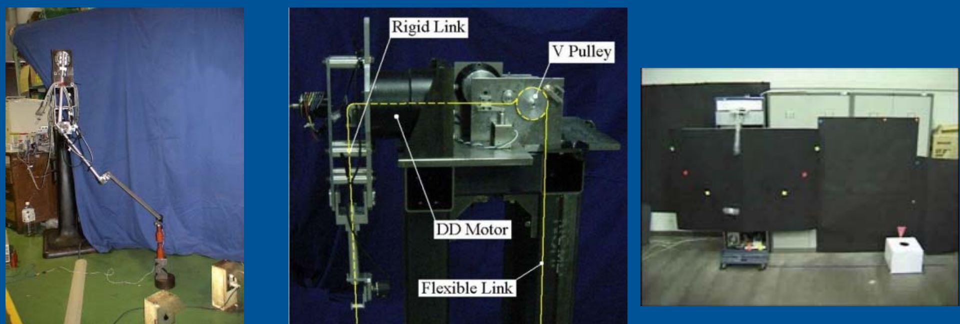
Flexure Revolute Joint



Brakes for Robots

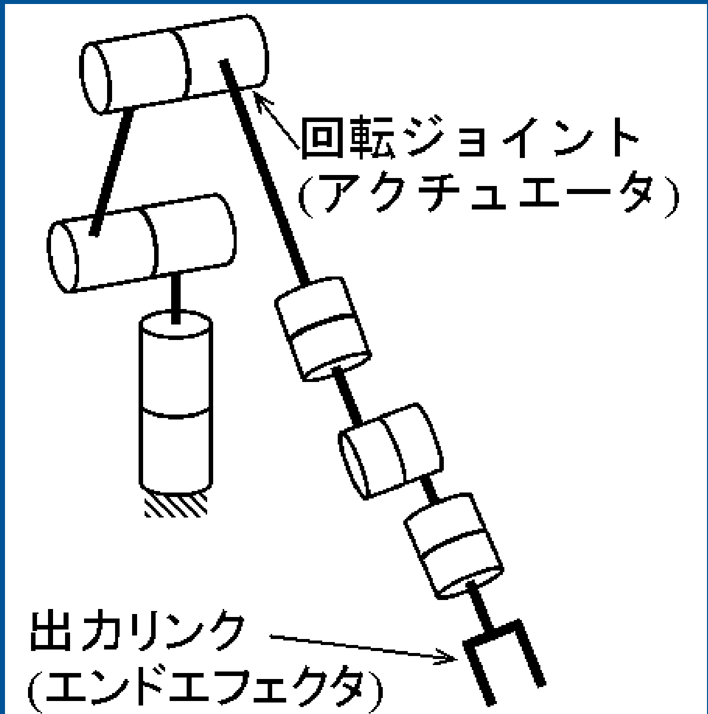


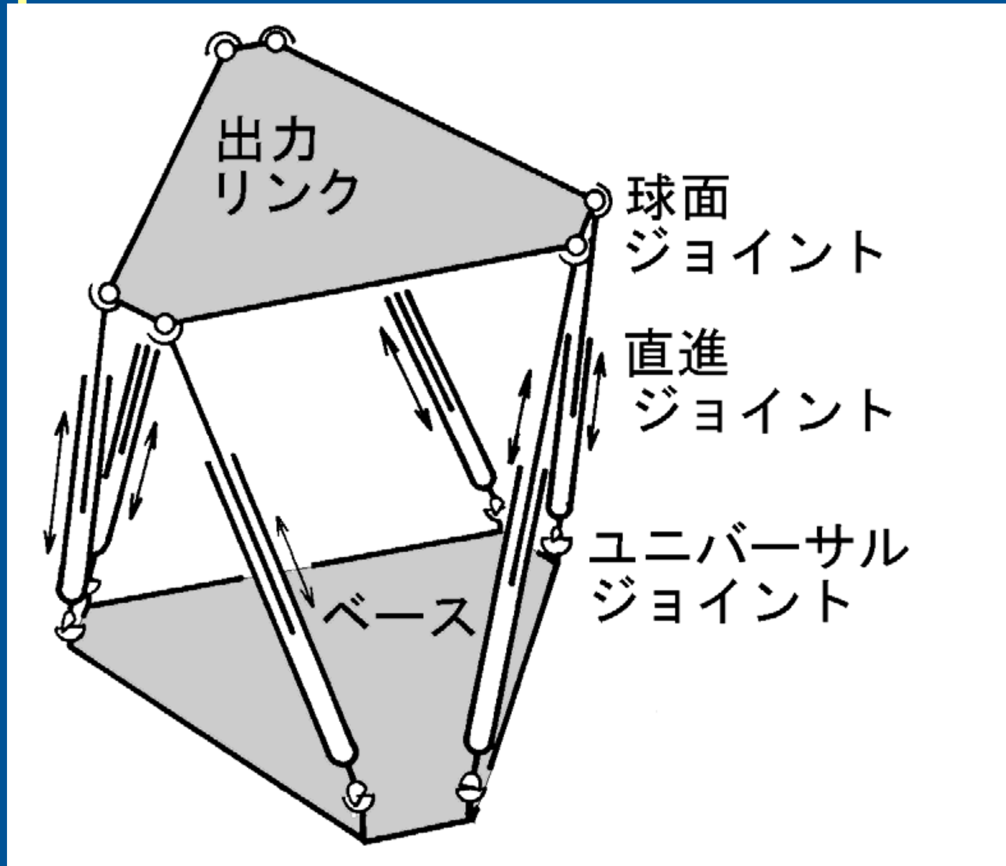
Linear Actuator



Under-actuated Manipulator

Serial Mechanism and Parallel Mechanism





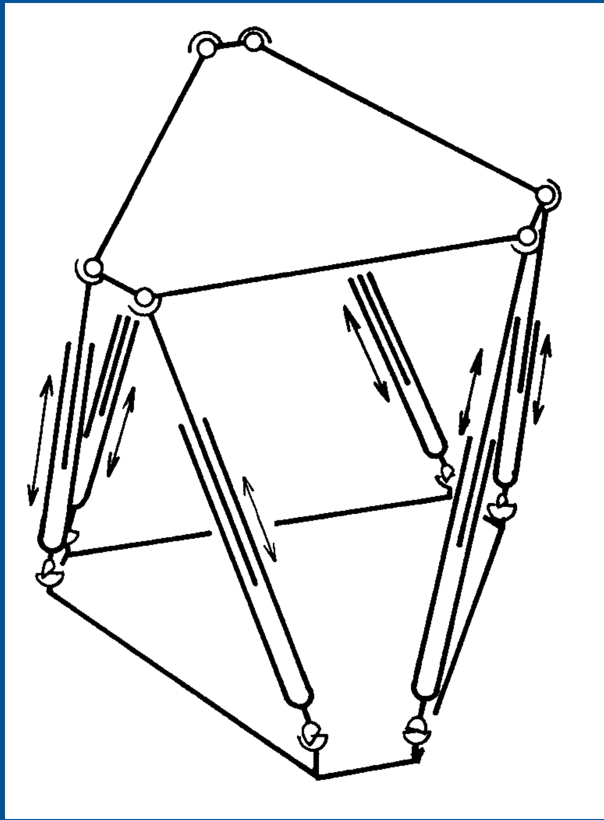
Serial Mechanism

All joints are active.

Parallel Mechanism

Only the prismatic joints are active.

Parallel Mechanism



Typical Parallel Mechanism
(Stewart-Gough platform)

Definition by Jean P. Merlet in “Parallel Robots”:

“A generalized parallel manipulator is a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains”, “A parallel robot is made up of an end-effector with *n* degrees of freedom, and of a fixed base, linked together by at least two independent kinematic chains. Actuation takes place through *n* simple actuators”, “Parallel robots for which the number of chains is strictly equal to the number of degrees of freedom of the end-effector are called fully parallel manipulators.”

Several kinematic structures (dof, arrangement of joints in kinematic chain, number of kinematic chains, etc)

Several applications: Machine tools, manipulators, coordinate measuring machine, motion simulator, positioning, etc.

Transmission Index and Singular Point of Parallel Manipulators (1989-2000)

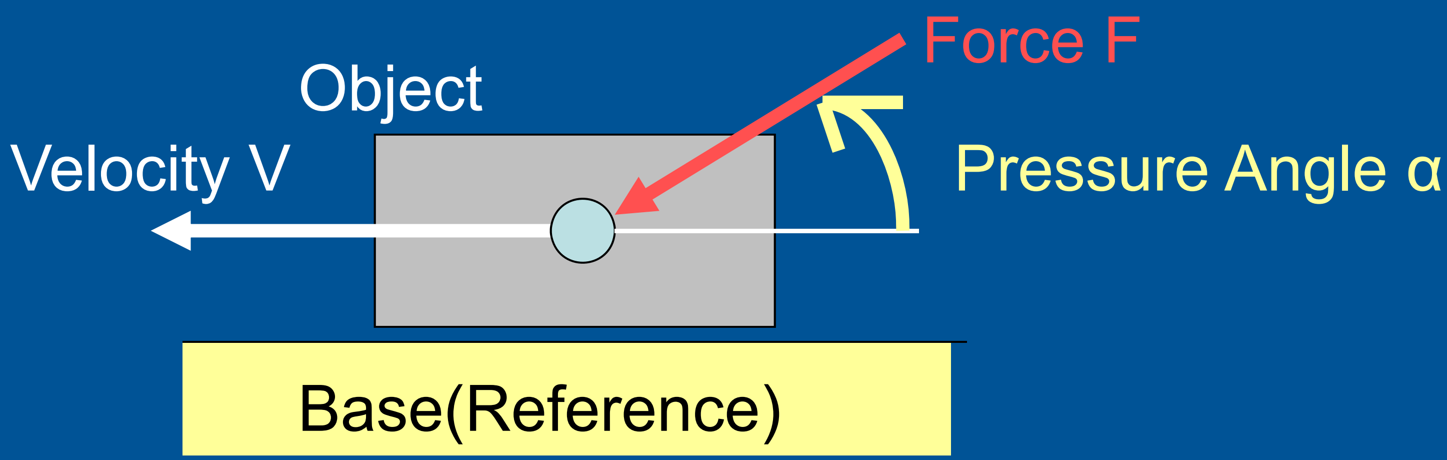
- ✓ Transmission Index for Fully Parallel Manipulators(1993-1995)
- ✓ Transmission Index for Wire-Driven Parallel Manipulators(1999)
- ✓ Determination of Singular Point by Means of Transmission Index(1994)
- ✓ Determination of Neighborhood/Vicinity of Singular Point(1995)

Observation of Singular Points(1989-1992)

Motion in Working Space

Behavior around Singular Points

Concept of Pressure Angle

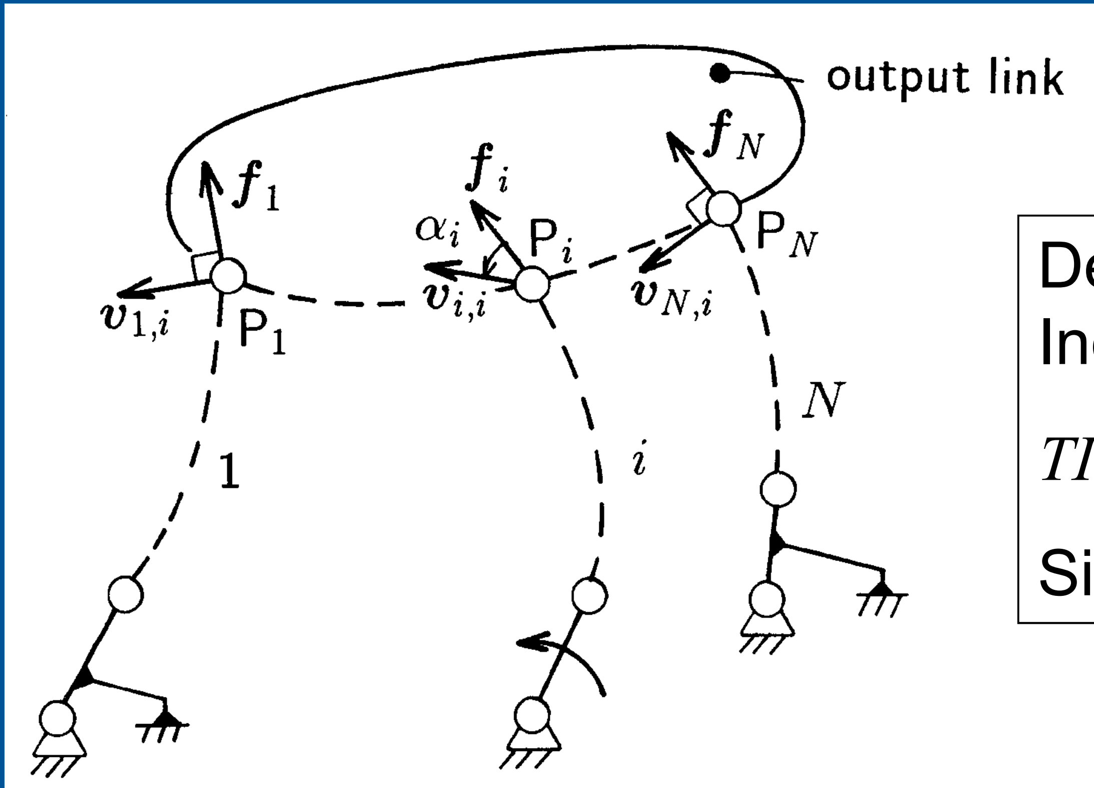


A simple case of a single dof mechanism

Only the component of F along V, Fcos α can be transmitted to the object. So, basic idea is to make the angle α as close to 0 deg as possible. When α=90 deg, it corresponds to a singular configuration(point).

Transmission Index for a single dof mechanism: TI=cos α

Transmission Index for Parallel Manipulators



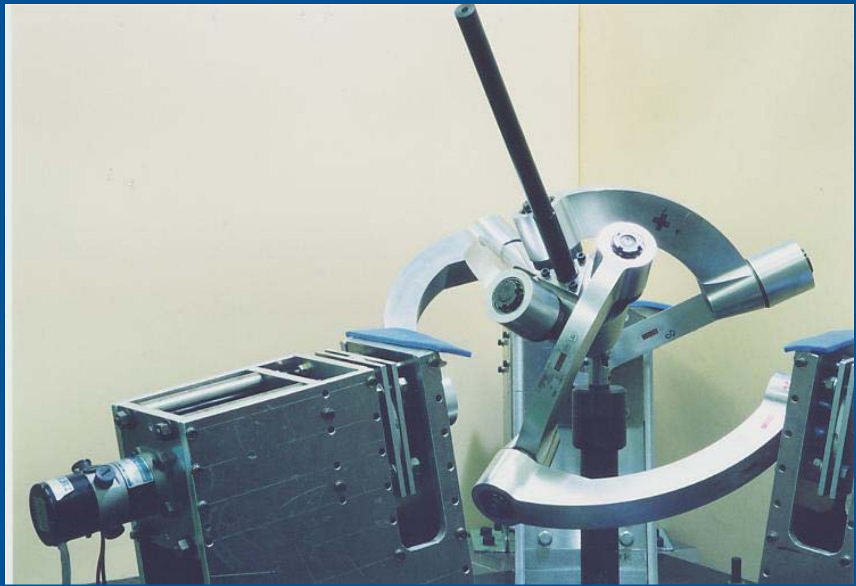
Definition of Transmission Index *TI*

$TI = \min(|\cos\alpha_1|, \cdots, \cos|\alpha_N|)$

Singular Point：$TI = 0$

All of the inputs except for that of i-th connecting chain among N chains of a parallel mechanism are locked. The direction of the force applied to the output link from each chain is geometrically determined. When the input joint of i-th chain is driven, the velocity and the force at the connection point form an angle as shown in the figure. This angle corresponds to the pressure angle. For N-dof mechanism, there exist N pressure angles.

Spherical Parallel mechanism with High Motion Transmissibility (1993)



Overview of prototype(1993)

Motion Transmissibility and collision between the links were considered in the design

Swing angle : ±65° ～75°

Repeatability:

±2～8 μm (arm length=200mm)

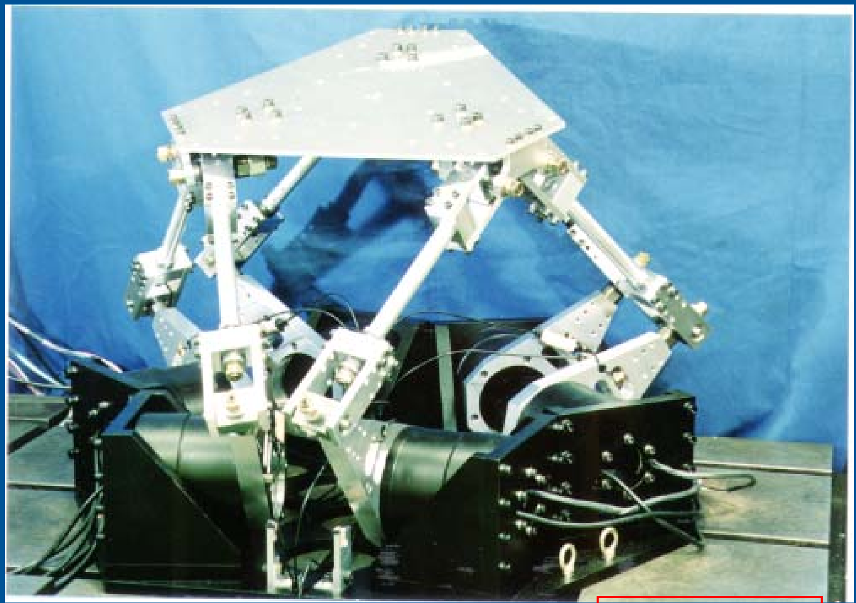
Absolute accuracy:0.043deg（Ave）,
0.33deg（worst）

Demonstration (Video)

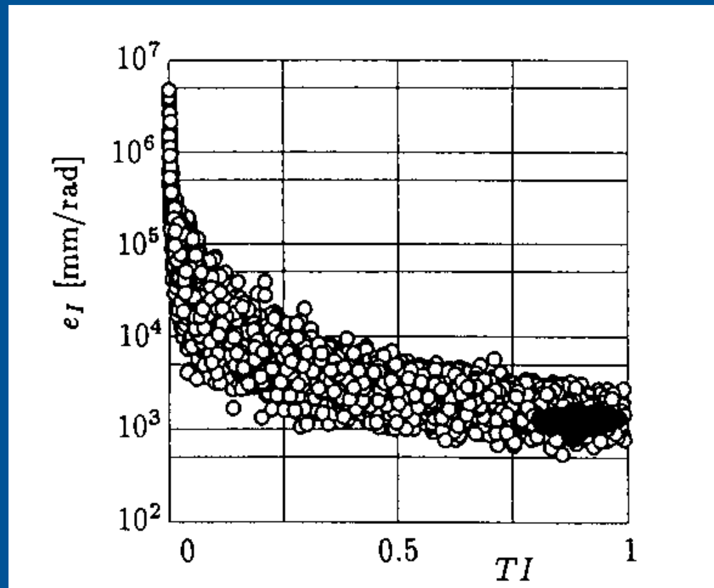
Reference

Yukio TAKEDA, Hiroaki FUNABASHI and Yasutaka SASAKI, Development of a Spherical In-parallel Actuated Mechanism with Three Degrees of Freedom with Large Working Space and High Motion Transmissibility (Evaluation of Motion Transmissibility and Analysis of Working Space), JSME International Journal, Series C, 39-3(1996,September), pp.541-548.

Spatial Parallel mechanism with High Motion Transmissibility (1993)



Prototype(1993) ビデオ

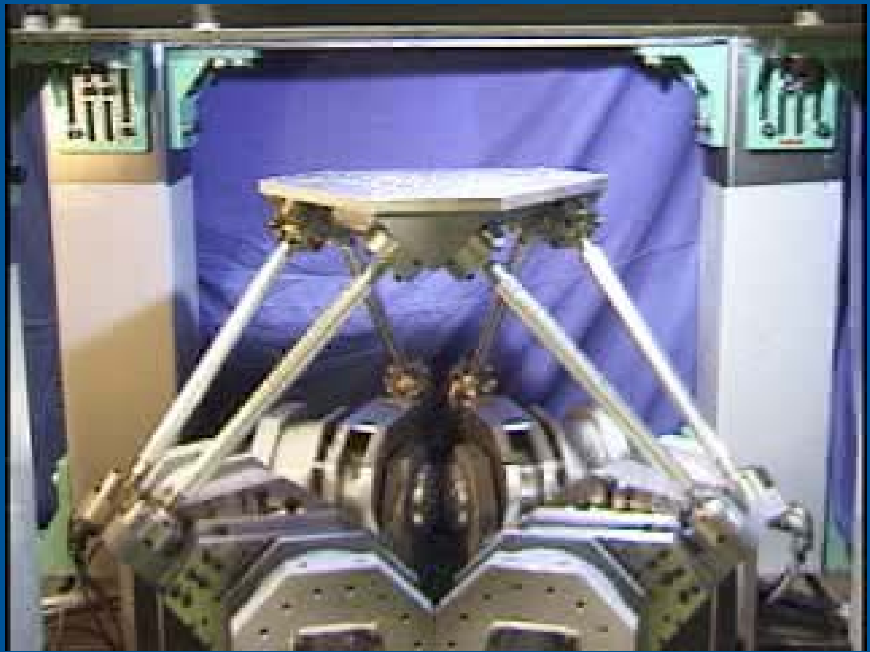


TI vs. output position error
（● : prototype）

Monte-Carlo technique was applied to the mechanism design of the prototype.

Kinematic Calibration of Parallel Manipulator

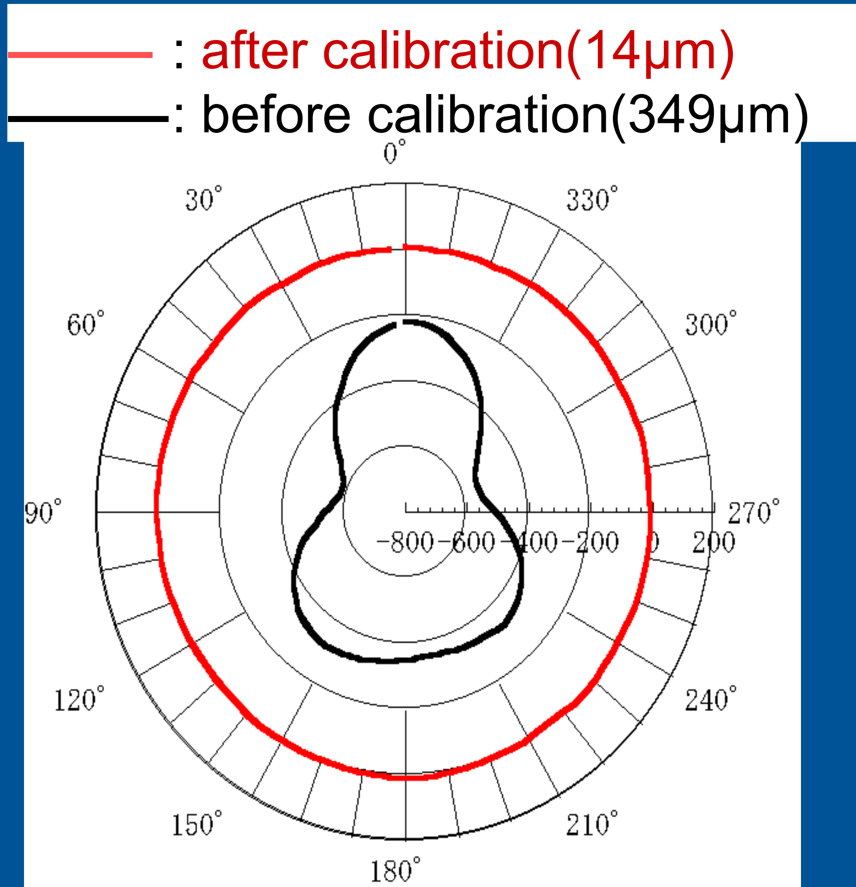
キャリブレーション研究(井本）



Experimental Apparatus

Basement : 1,200 × 1,200mm^2

Workspace : 650 × 650 × 350mm^3
67 × 60 × 76 deg^3



Effect of calibration

Video

Y.Takeda, et al, A DBB-Based Kinematic Calibration Method for In-Parallel Actuated Mechanisms Using a Fourier Series, J. Mech. Des. 126(5), 856-865 (Oct 28, 2004) (10 pages), doi:10.1115/1.1767822

Validation of Calibration

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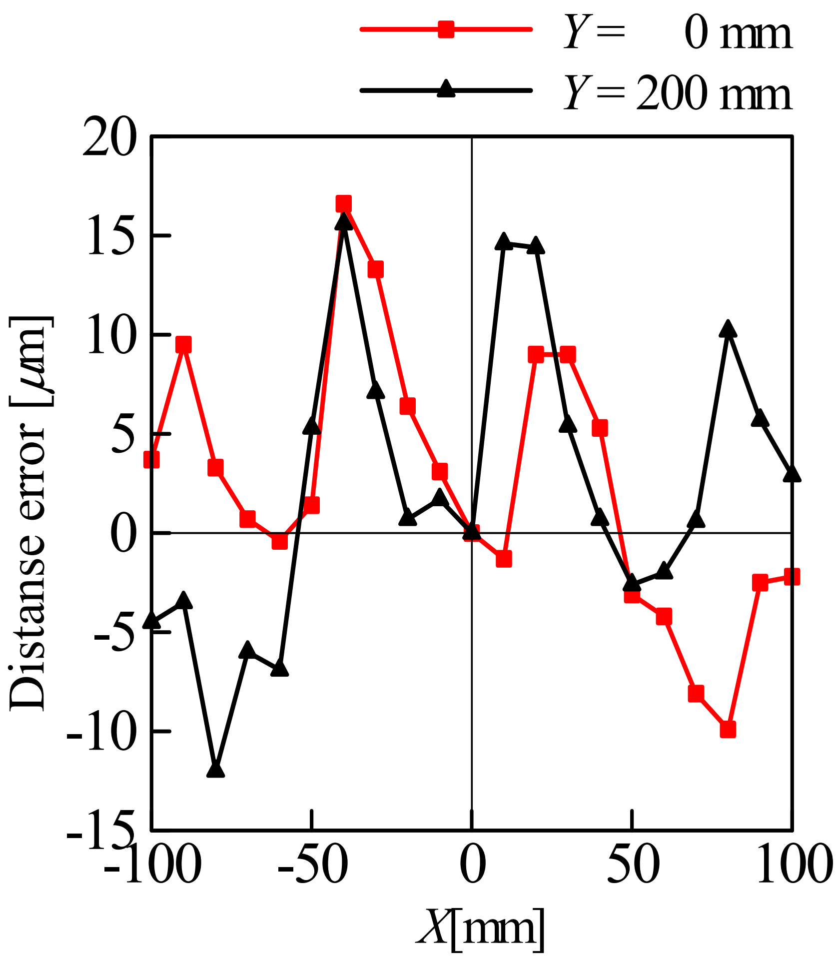
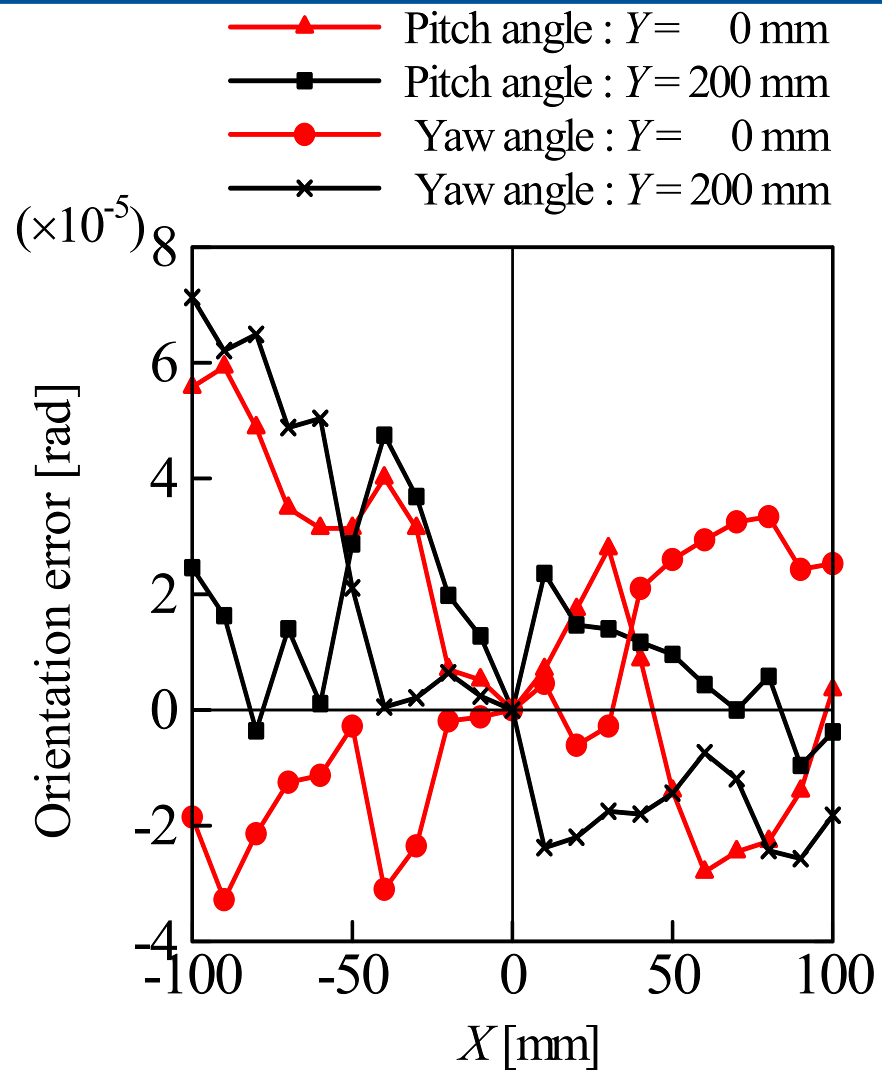
Mechanical Systems Design Lab.





Distance error

Pitch and Yaw angle error

References-Motion Transmissibility

1. Takeda, Y. and Funabashi, H., A Transmission index for in-parallel wire-driven mechanisms, JSME International Journal Series C, Vol. 44, No. 1, pp. 180-187, 2001.
2. Takeda, Y., Funabashi, H. and Ichimaru, H., Development of spatial in-parallel actuated manipulators with six degrees of freedom with high motion transmissibility, JSME International Journal, Series C, Vol. 40, No. 2, pp. 299/308, 1997.
3. Takeda, Y. and Funabashi, H., Kinematic and static characteristics of in-parallel actuated manipulators at singular points and in their neighborhoods, JSME International Journal, Series C, Vol. 39, No. 1, pp. 85-93, 1996.
4. Takeda, Y., Funabashi, H. and Sasaki, Y., Development of a spherical in-parallel actuated mechanism with three degrees of freedom with large working space and High motion transmissibility (evaluation of motion transmissibility and analysis of working space), JSME International Journal, Series C, Vol. 39, No. 3, pp. 541-548, 1996.
5. Takeda, Y. and Funabashi, H., Motion transmissibility of in-parallel actuated manipulators, JSME International Journal, Series C, Vol. 38, No. 4, pp. 749-755, 1995.

Kinematic Design of Compensatable Parallel Manipulators

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Director, Super-Mechano System Innovation & Development Center
Tokyo Institute of Technology, Japan
http://www.mech.titech.ac.jp/~msd/, http://www.sms.titech.ac.jp/
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Presented at Robotics PPRIME Forum 2014, November 6, 2014, University of Poitiers, France

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Tokyo Institute of Technology
Mechanical Systems Design Lab.

Introduction

Precise Manipulators:

- ➢ with full dof(spatial: 6, planar: 3, spherical: 3)
- ➢ with limited dof (lower dof)
  (pure rotational-motion/translational-motion manipulator)

Requirements:

- large stroke & high resolution(accuracy)
- low parasitic motion

Problems:

- ☐ low dynamic range of actuator in displacement
- ☐ inevitable error of kinematic parameters and their effect on the output error
- ☐ umcompensatable error in limited-dof manipulator

Solutions:

- ✓ use of redundancy for compensation with redundant actuators for gross and fine motions
- ✓ use of redundancy for compensation with decoupled mechanism for limited-dof manipulator
- ✓ kinematic design(optimization) based on the sensitivity

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Application targets of precise robot manipulators

Applications

- Position adjusting machine for connection of optical fibers
- Fabrication machine of master disk for DVD
- Micro/nano machines

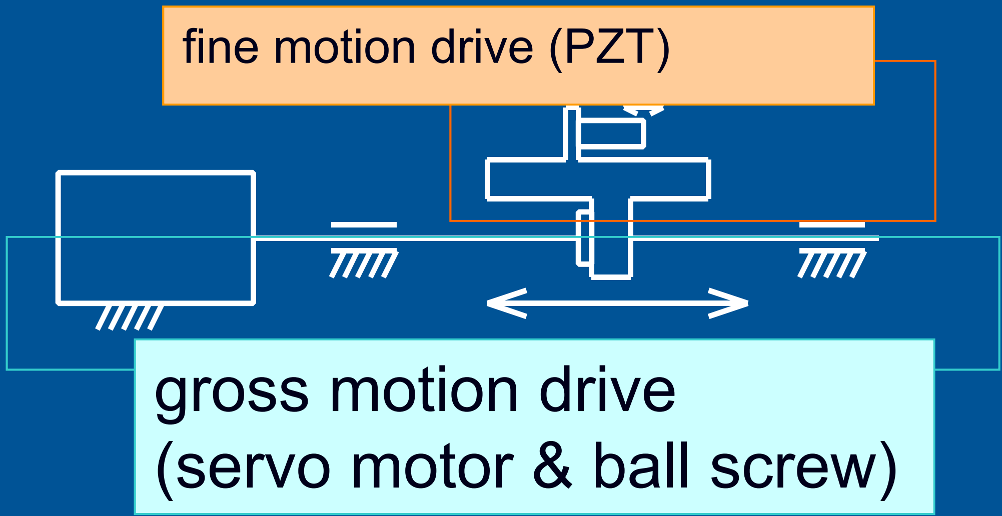
Required performance

Stroke : 50～100mm
Position Resolution : 10～50nm

} In 3D space

A solution to achieve a large stroke and fine resolution

Gross-fine drive



An example of a gross-fine drive for a single axis motion

Drawbacks

If a positioning robot with multiple-dof is constructed by ***serially connecting*** the drives , it must be ***heavy***.

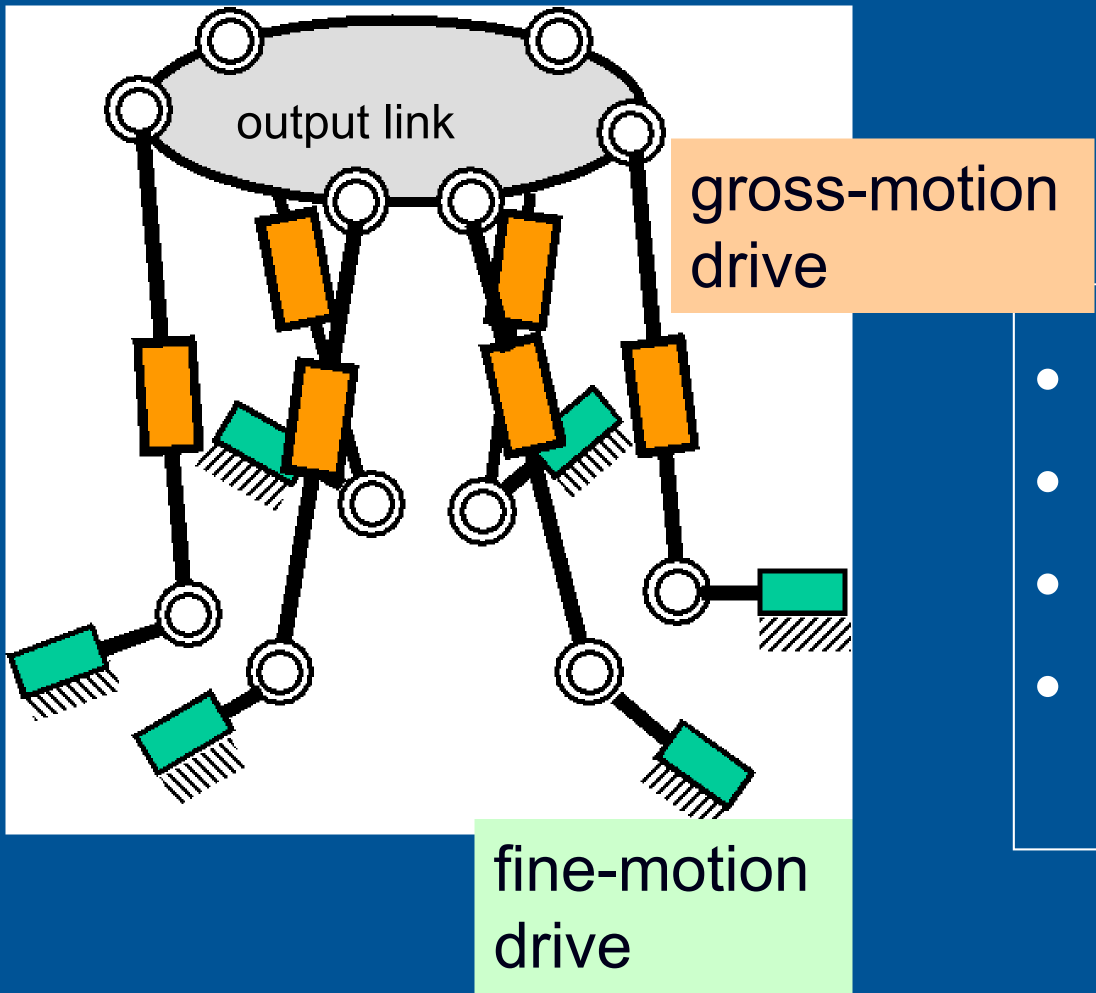
⇩

Slow motion, error due to deformation, residual vibration, etc.

Another solution is needed.

Redundant Parallel Manipulator

Our proposal:



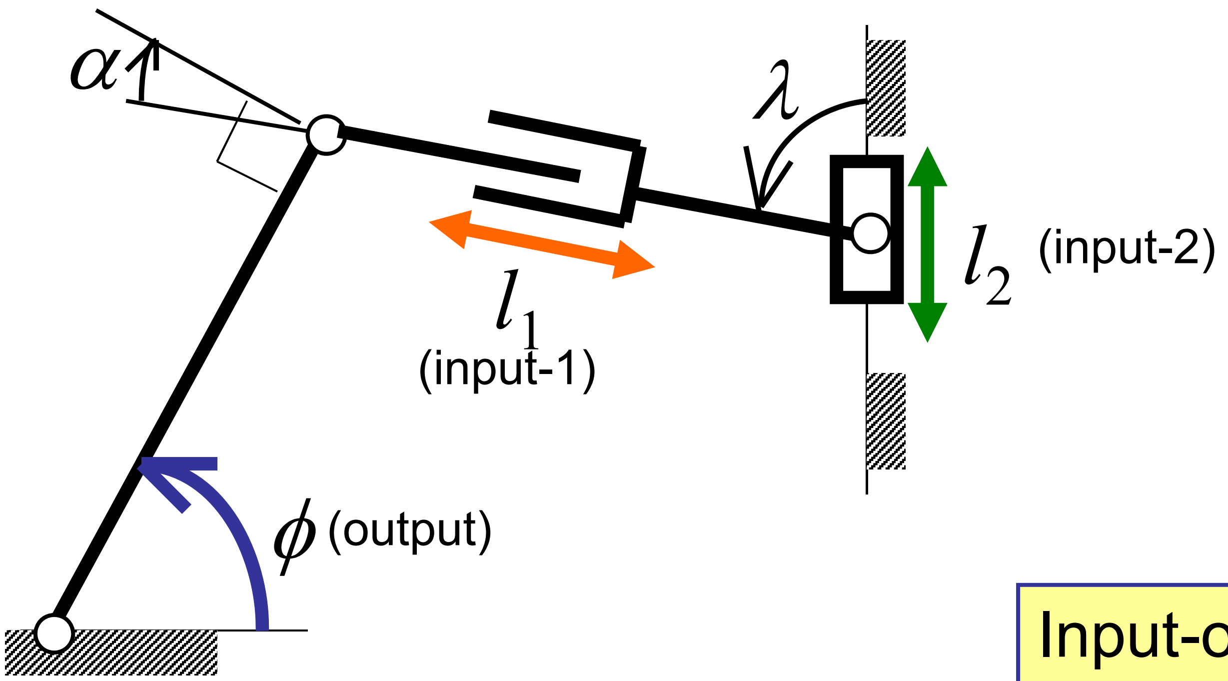
Advantages

- light inertia
- fast motion
- high precision
- high rigidity

  ect.

A redundant parallel manipulator with six-dof

Basic Idea to Simultaneously Realize Large Workspace and Fine Resolution

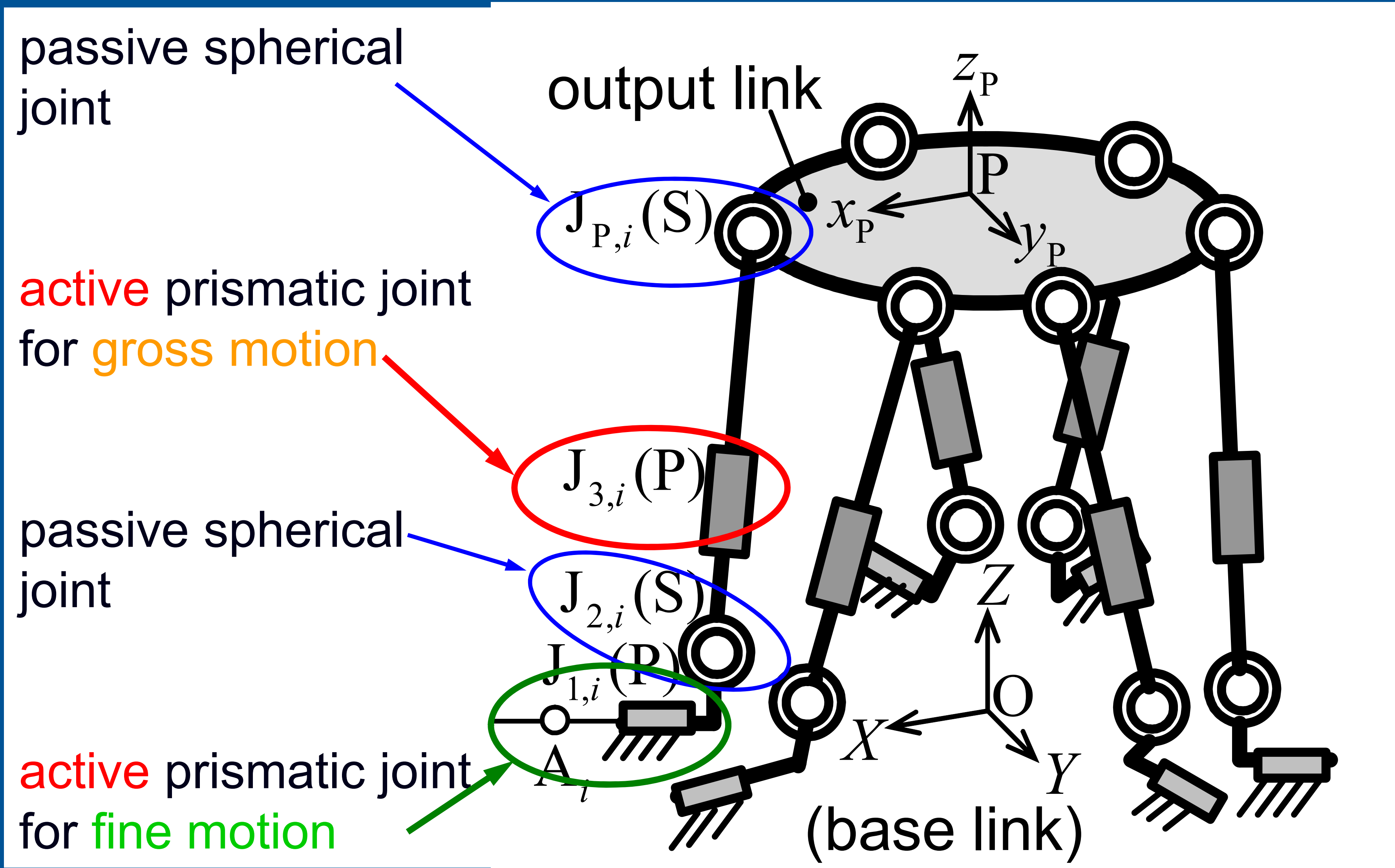


5-bar mechanism with two inputs and a single output (example)

Input-output relationship in infinitesimal displacement

$$\Delta\phi = \frac{c(\Delta l_1 + \Delta l_2 \cos\lambda)}{\cos\alpha}$$

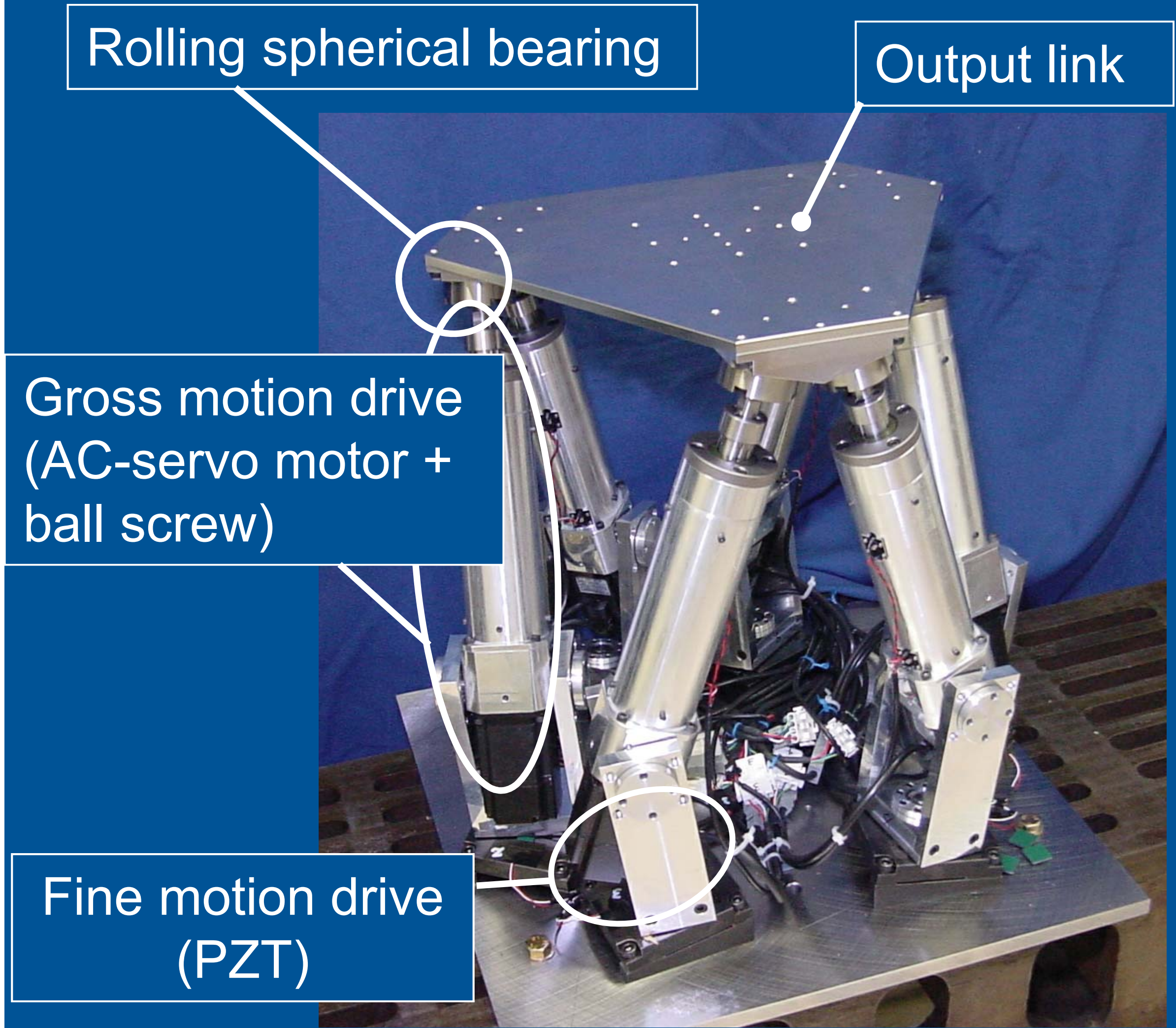
Mechanism configuration



Redundant spatial parallel mechanism with six active joints for gross motion and six active joints for fine motion

Our prototype(2001)

Tokyo Institute of Technology
Mechanical Systems Design Lab.



Workspace

(T) X, Y : ±40mm
Z : ±20mm
(R) X, Y, Z : ±10°

Desired resolution

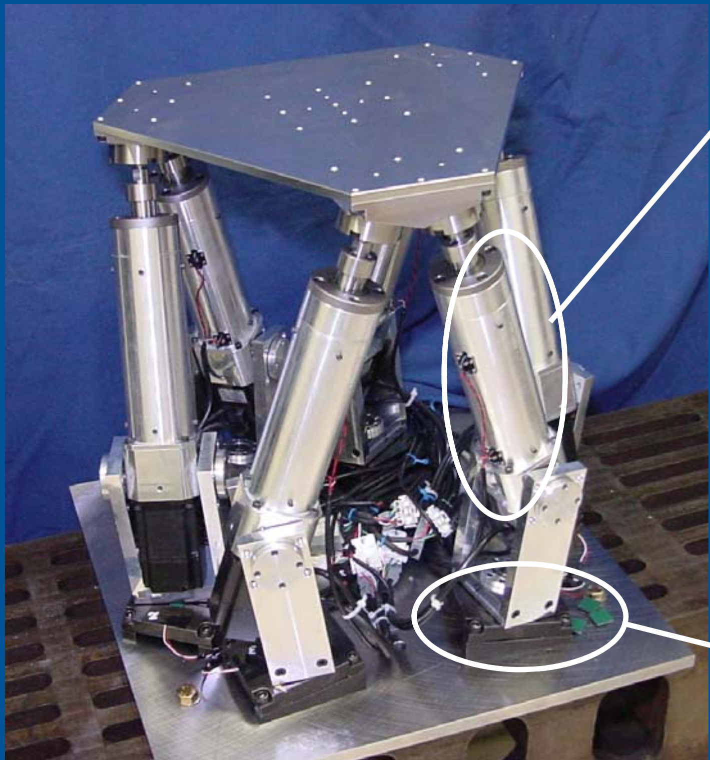
Trans. : 20nm

Rotat. : 0.2μrad

Size

540mm × 540mm × 600mm^3

Prototype manipulator



Overview of the prototype

Workspace:
80(X) x 80(Y) x 40(Z) mm
20 deg (all direction)
Resolution:
20 nm (trans.), 0.2μ rad (rotat.)

Specs. of gross motion drive system

AC servo actuator	
Rated power	200 W
Rated speed	3,000 rpm
Resolution of encoder	16 bit
Ball screw	
Diameter of shaft x lead	10 x 25 mm
Dynamic load capacity	2,130 N
Static load capacity	3,640 N
Maximum speed	3,000 rpm

Specs. of fine motion drive system (PZT)

Stroke	12.3 ±3.5μm
Applied voltage	100V
Size	15.7 x 15.7 x 20 mm

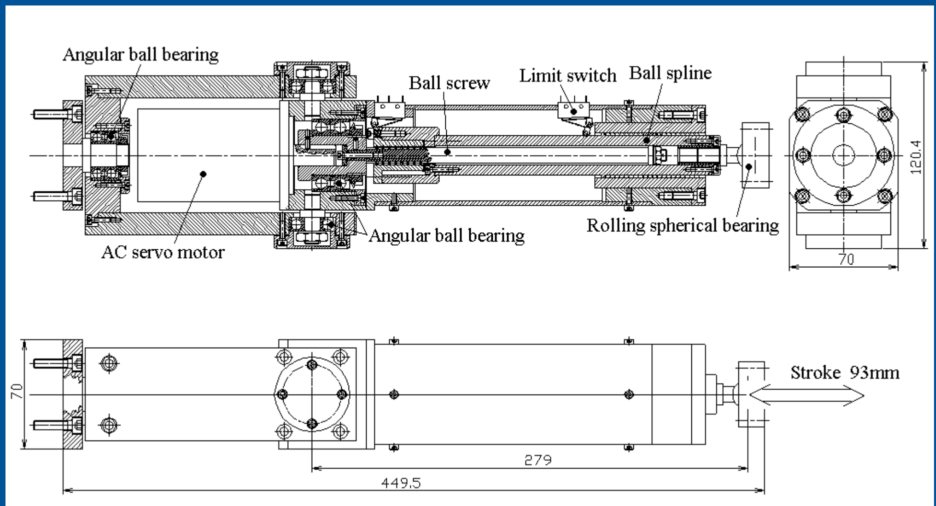
Performance of drive systems

	Gross motion	Fine motion
Stroke	93 mm	±7μm
Resolution	0.2 μm	4 nm

Gross-motion drive

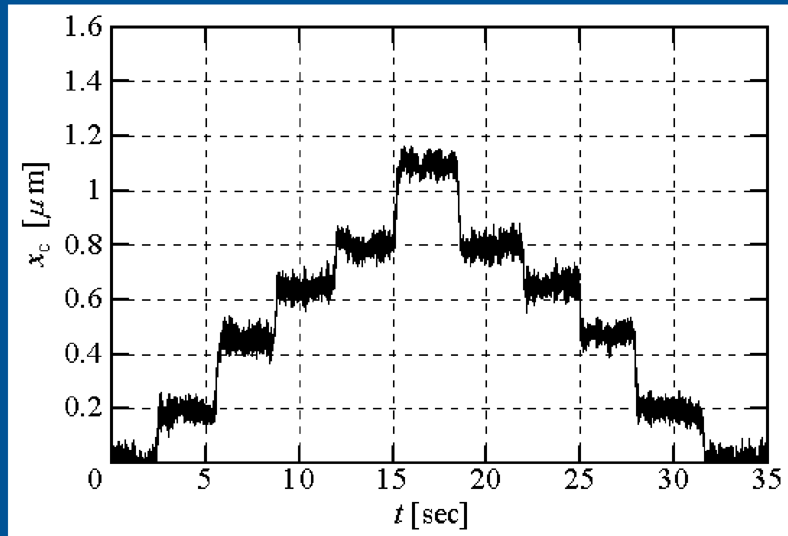
Stroke =93mm

Overview



Composition

(AC-Servo Motor & Ball Screw of Lead 2.5mm)

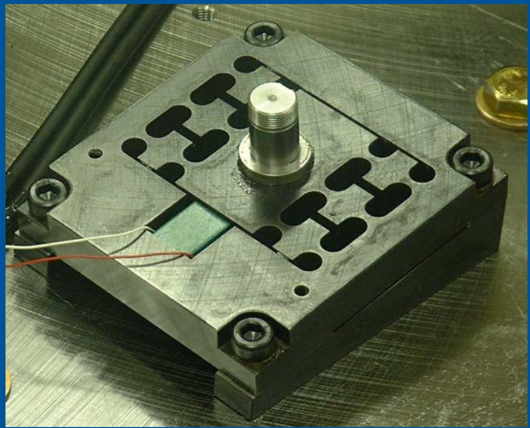


Step response(0.2μm)

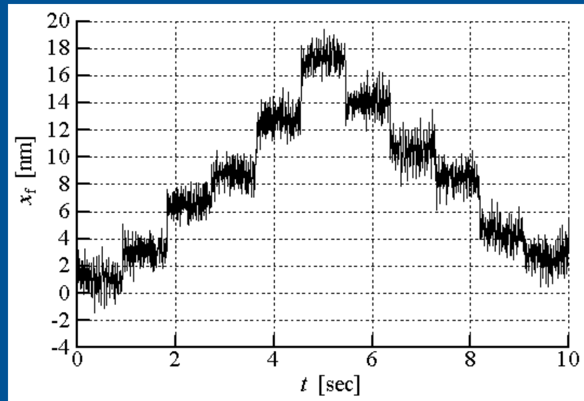
Resolution

Realized (0.2 μm) < Design (1μm)

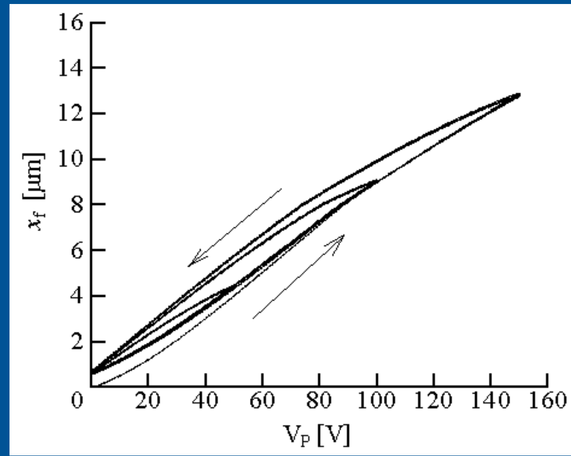
Fine-motion drive



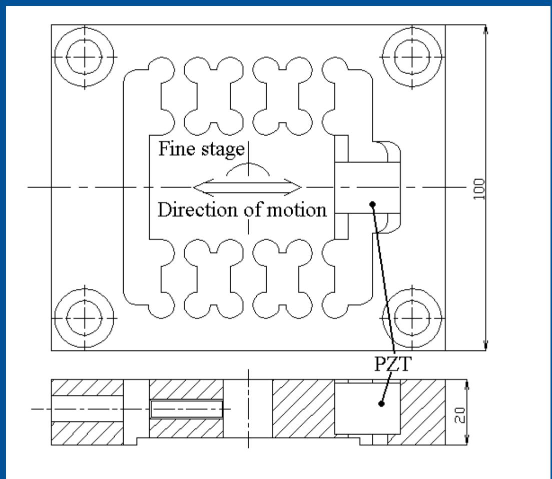
Overview



Step response (4nm)



Max. stroke



Composition
(PZT & flexure hinges)

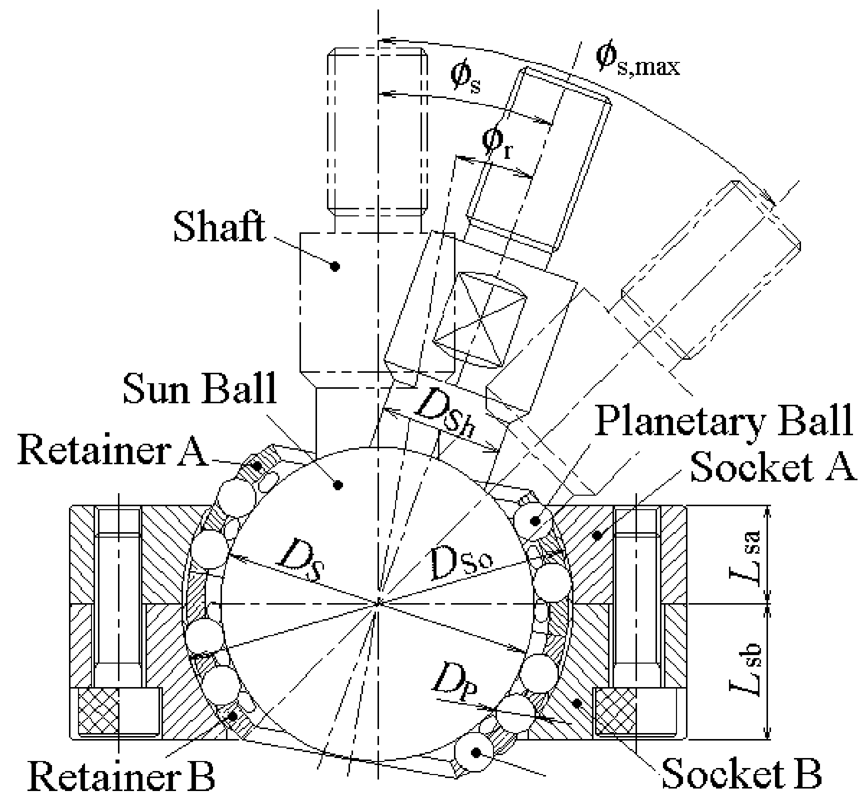
Resolution

Realized (4nm) < Design (10nm)

Stroke

Realized (10μm) = Design (10μm)

Rolling spherical bearing



Composition

Specifications

(SRJ016T: Product of Hephaist Seiko Co, Ltd.)

Max. swing angle

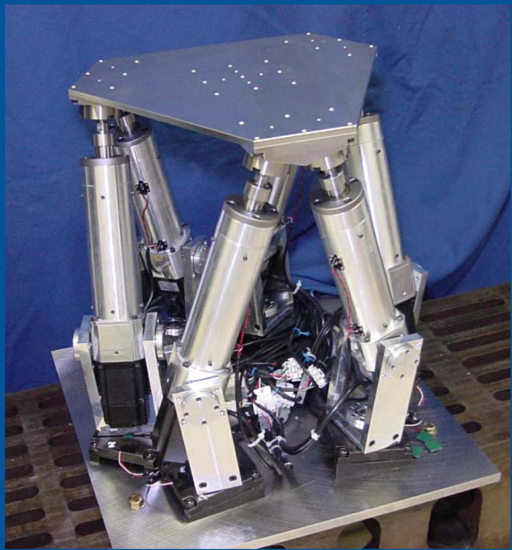
±30deg

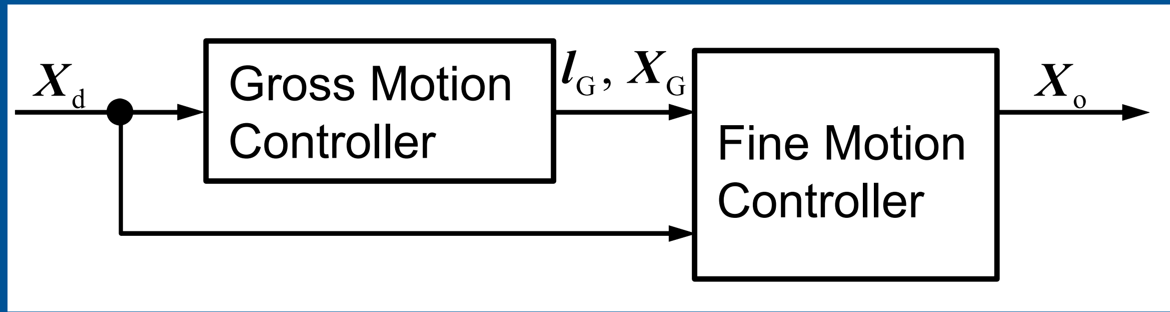
Diameter of the sun ball

25.4mm

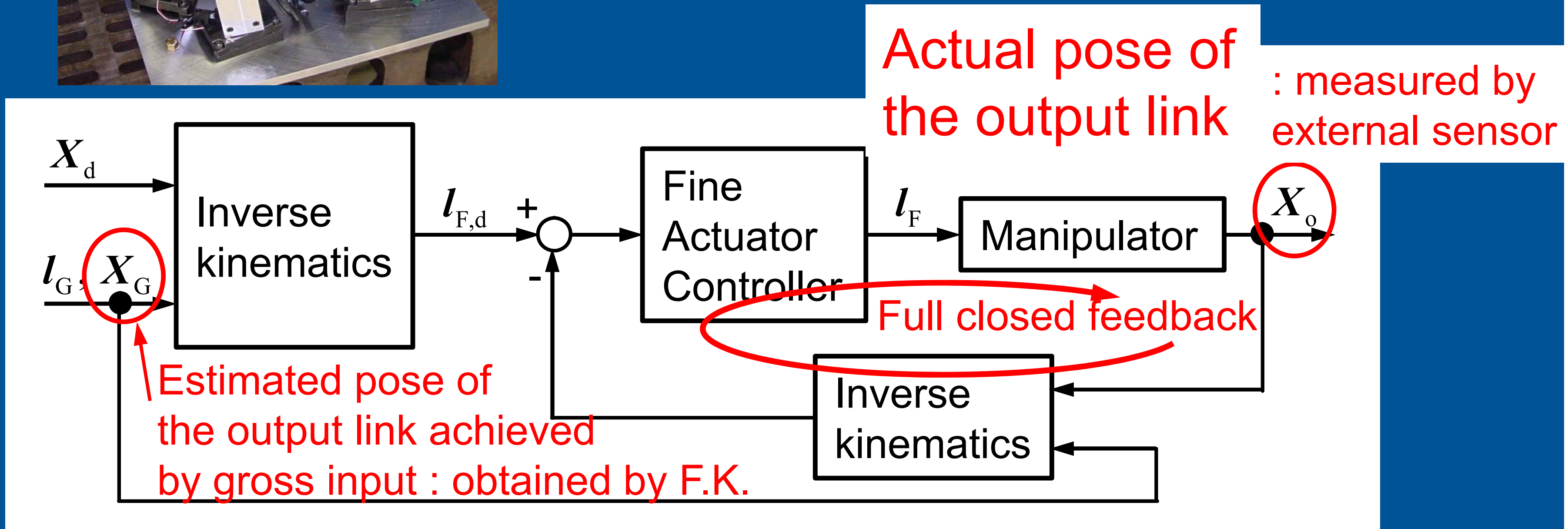
Movie

Control system of the prototype manipulator





Composition of the control system



Composition of the fine-motion controller

Inverse kinematics

Given : $\boldsymbol{p}$ (position of the reference point and T (orientation) of the output link

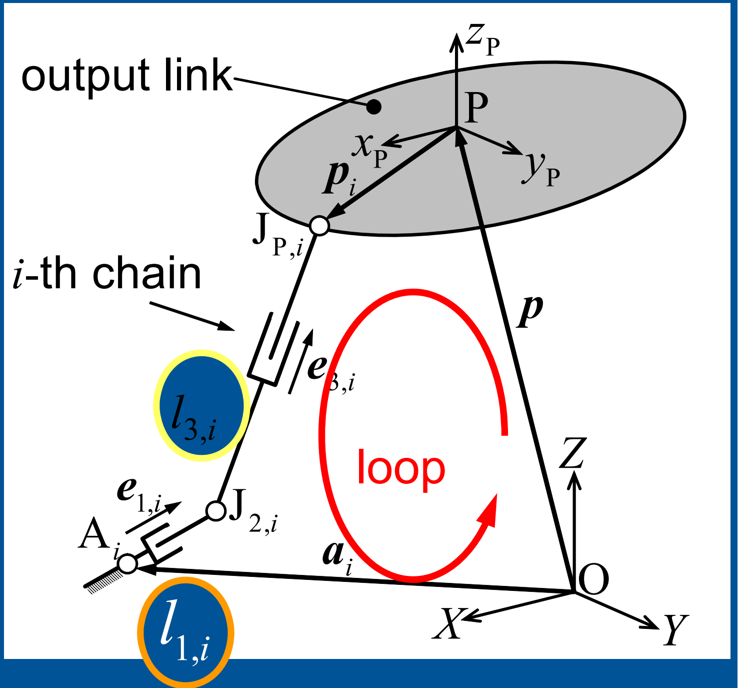
Obtain : input displacements $l_{1,i}$ and $l_{3,i}$ (i=1,2,…, 6) for gross and fine motions

Closed loop equation:

$$\overrightarrow{\mathrm{J}_{2,i}\mathrm{J}_{\mathrm{P},i}} = l_{3,i}\boldsymbol{e}_{3,i} = \boldsymbol{p} + T^{\mathrm{T}}\boldsymbol{p}_i - \boldsymbol{a}_i - l_{1,i}\boldsymbol{e}_{1,i}$$

T: 3×3 rotation matrix

$$l_{3,i}^2 = \boldsymbol{p}^2 + \boldsymbol{p}_i^2 + \boldsymbol{a}_i^2 + l_{1,i}^2 - 2\boldsymbol{p}_i^{\mathrm{T}}T(\boldsymbol{a}_i + l_{1,i}\boldsymbol{e}_{1,i}) + 2\boldsymbol{p}^{\mathrm{T}}(T^{\mathrm{T}}\boldsymbol{p}_i - \boldsymbol{a}_i - l_{1,i}\boldsymbol{e}_{1,i}) + 2l_{1,i}\boldsymbol{a}_i^{\mathrm{T}}\boldsymbol{e}_{1,i}$$



Vector representation of one connecting chain

This scalar equation has two unknown parameters (input displacements for gross and fine motions) in each chain for a specified pose of the output link.

Inverse kinematics

Closed loop equation:

$$\overrightarrow{\mathrm{J}_{2,i}\mathrm{J}_{\mathrm{P},i}} = l_{3,i}\boldsymbol{e}_{3,i} = \boldsymbol{p} + T^{\mathrm{T}}\boldsymbol{p}_i - \boldsymbol{a}_i - l_{1,i}\boldsymbol{e}_{1,i}$$

T: 3×3 rotation matrix

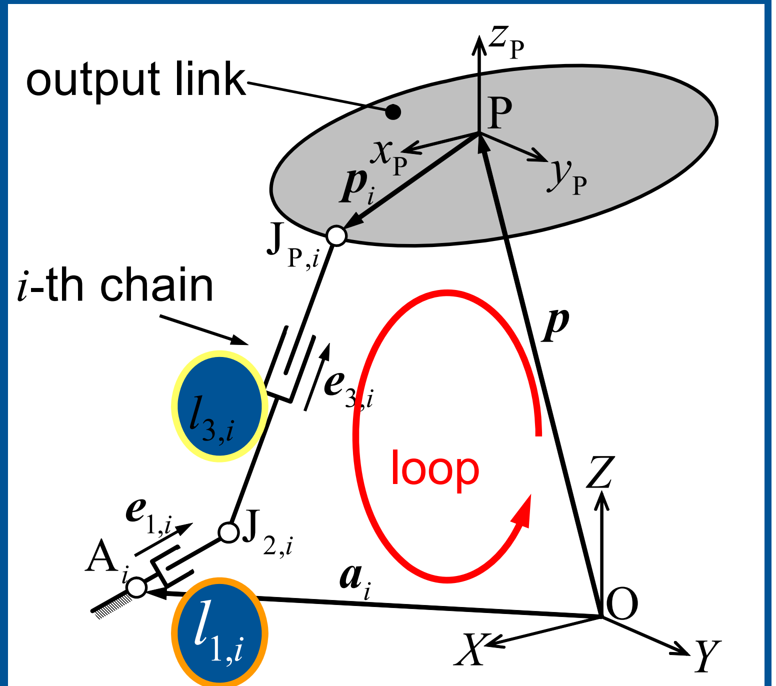
Solution of input displacement $l_{3,i}$:

$$l_{3,i}^2 = \boldsymbol{p}^2 + \boldsymbol{p}_i^2 + \boldsymbol{a}_i^2 + l_{1,i}^2 - 2\boldsymbol{p}_i^{\mathrm{T}}T(\boldsymbol{a}_i + l_{1,i}\boldsymbol{e}_{1,i}) + 2\boldsymbol{p}^{\mathrm{T}}(T^{\mathrm{T}}\boldsymbol{p}_i - \boldsymbol{a}_i - l_{1,i}\boldsymbol{e}_{1,i}) + 2l_{1,i}\boldsymbol{a}_i^{\mathrm{T}}\boldsymbol{e}_{1,i}$$

$l_{1,i}$: predetermined standard value is given

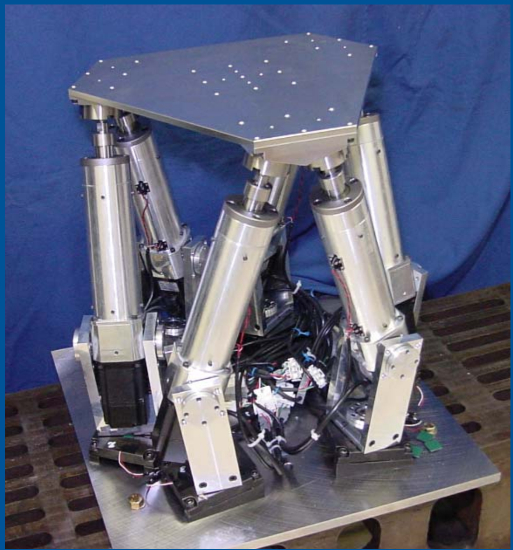
Solution of input displacement $l_{1,i}$:

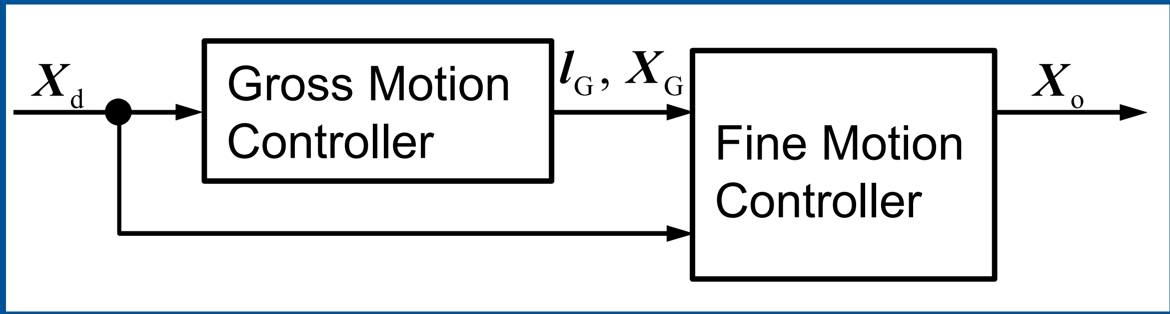
$$l_{1,i}^2 + 2(\boldsymbol{a}_i^{\mathrm{T}} - \boldsymbol{p}^{\mathrm{T}} - \boldsymbol{p}_i^{\mathrm{T}}T)\boldsymbol{e}_{1,i}l_{1,i} + \boldsymbol{p}^2 + \boldsymbol{p}_i^2 + \boldsymbol{a}_i^2 + 2\boldsymbol{p}^{\mathrm{T}}(T^{\mathrm{T}}\boldsymbol{p}_i - \boldsymbol{a}_i) - 2\boldsymbol{p}_i^{\mathrm{T}}T\boldsymbol{a}_i - l_{3,i}^2 = 0.$$



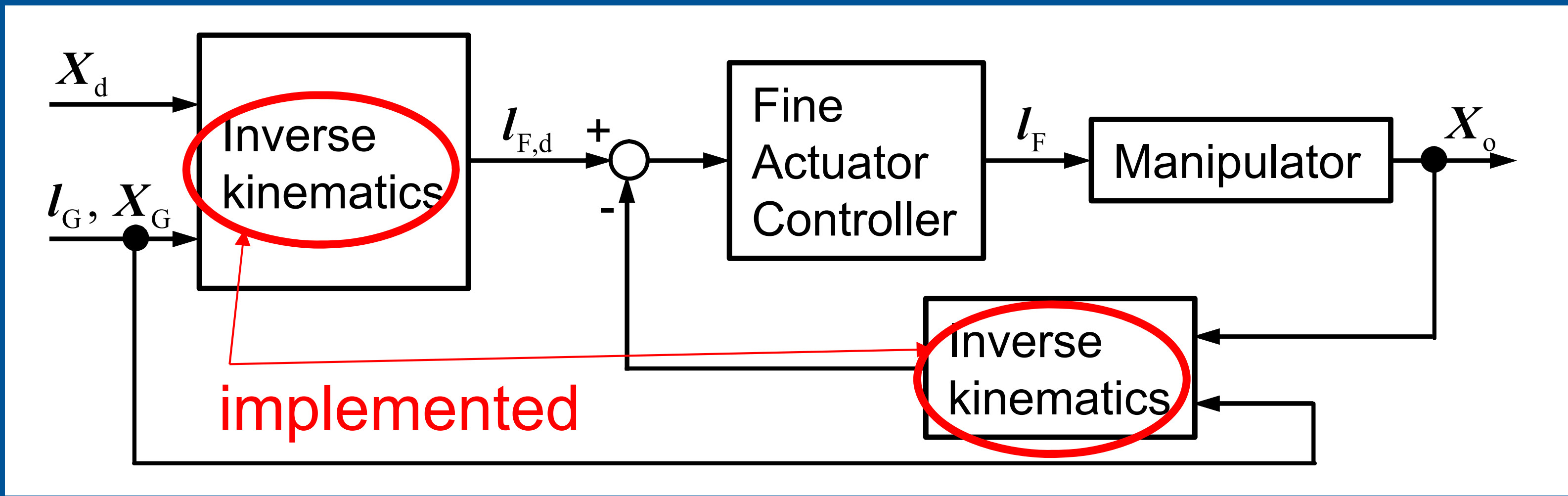
Vector representation of one connecting chain

Control system of the prototype manipulator





Composition of the control system



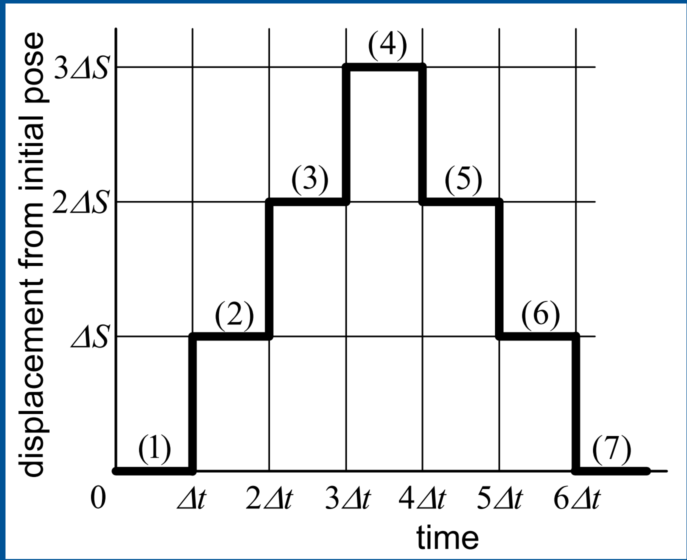
Composition of the fine-motion controller

Experimental investigations

Exp.1 :Successive fine step motion around an initial pose was given as a desired output motion to investigate resolution

Measurement of fine displacement:

Capacitive displacement sensor (ST-3512, Iwatsu Co., Ltd., measurement resolution : 6nm)



Change of desired pose with respect to time

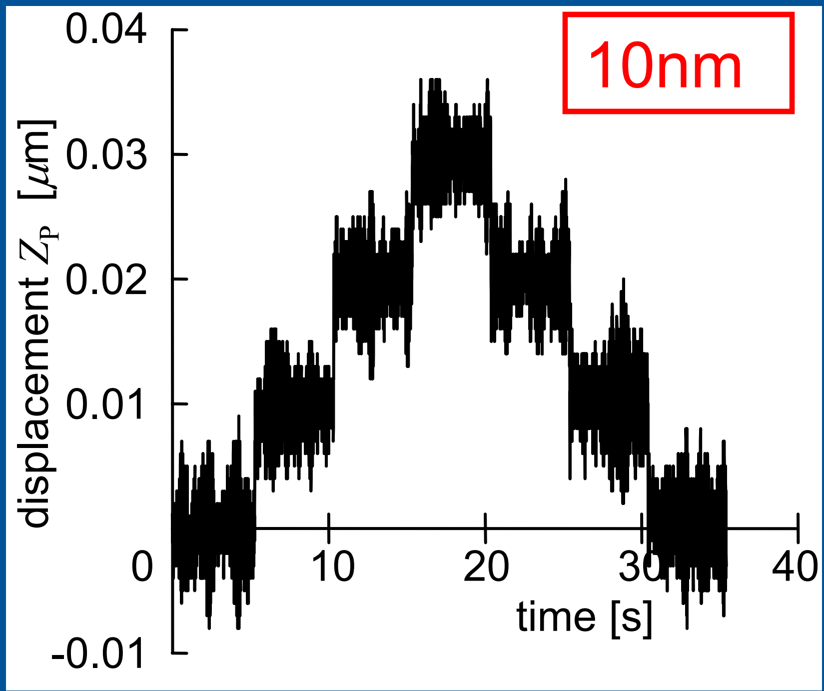
Cases of experiments (Zc:central Z coordinate)

No.	Initial position	Type of motion	Direction	Step magnitude
1	(0,0,Zc) [mm]	Trans.	Z	10 nm
2	(0,40,Zc) [mm]	Rotat.	Z	0.5 μrad
3	(0,0,Zc+20) [mm]	Trans.	Y	20 nm
4	(0,0,Zc) [mm]	Rotat.	X	1 μrad

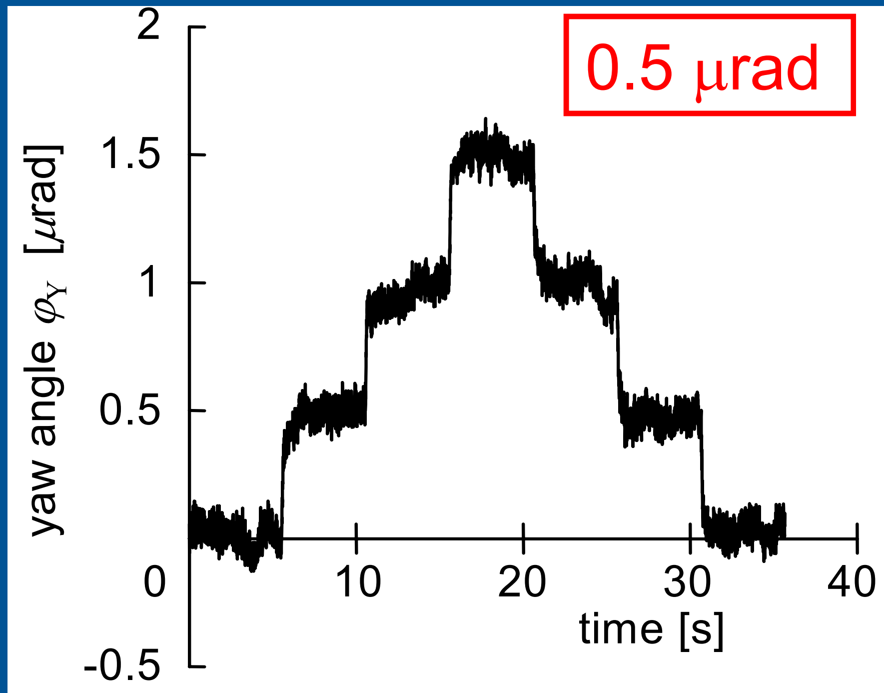
Experimental investigations

Exp.1 :Successive fine step motion around a pose

Results of experiments:



(1) Z direction translation, at (0,0,Zc) mm



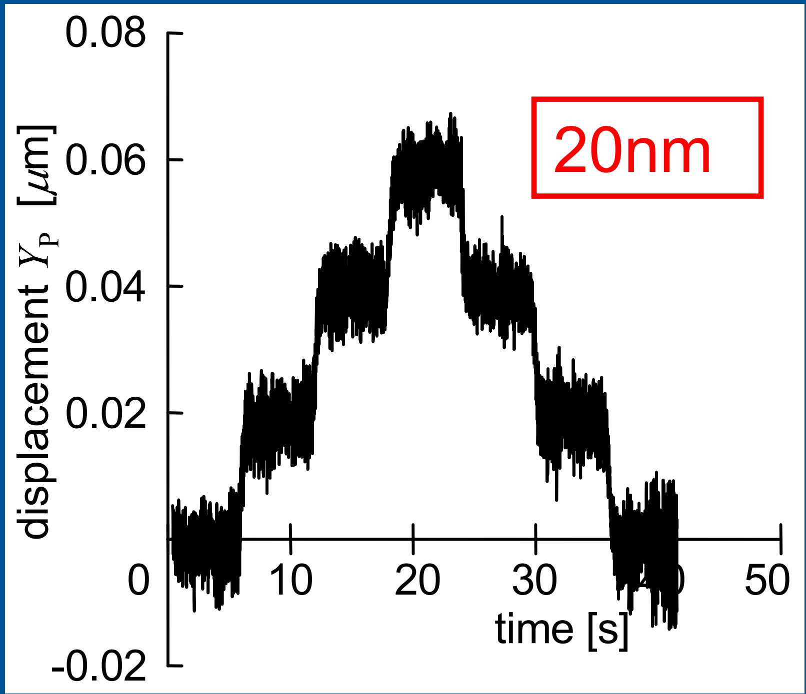
(2) Z direction, rotation, at (0,40,Zc) mm

It is known from these figures that successive step motions were successfully achieved for very fine steps.

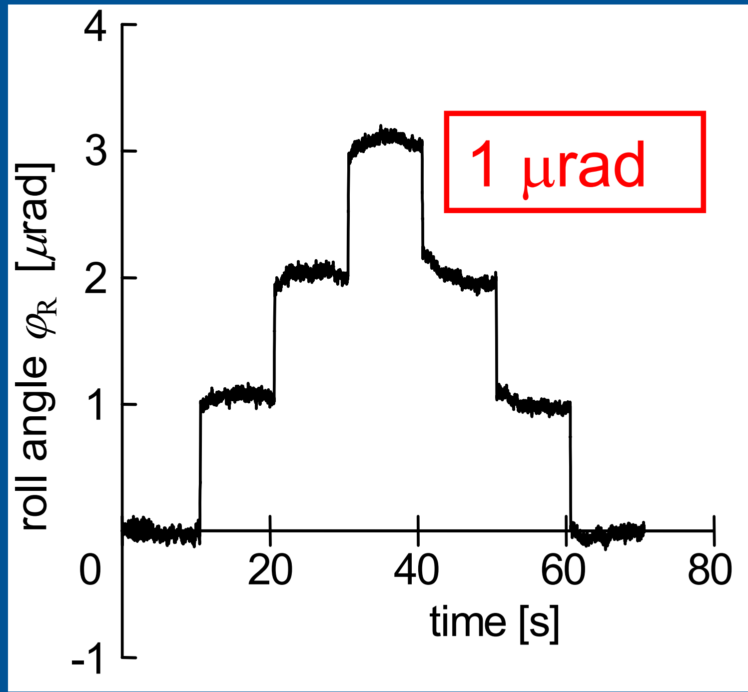
Experimental investigations

Exp.1 :Successive fine step motion around a pose

Results of experiments:



(3) Y direction translation, at (0,0,Zc+20) mm



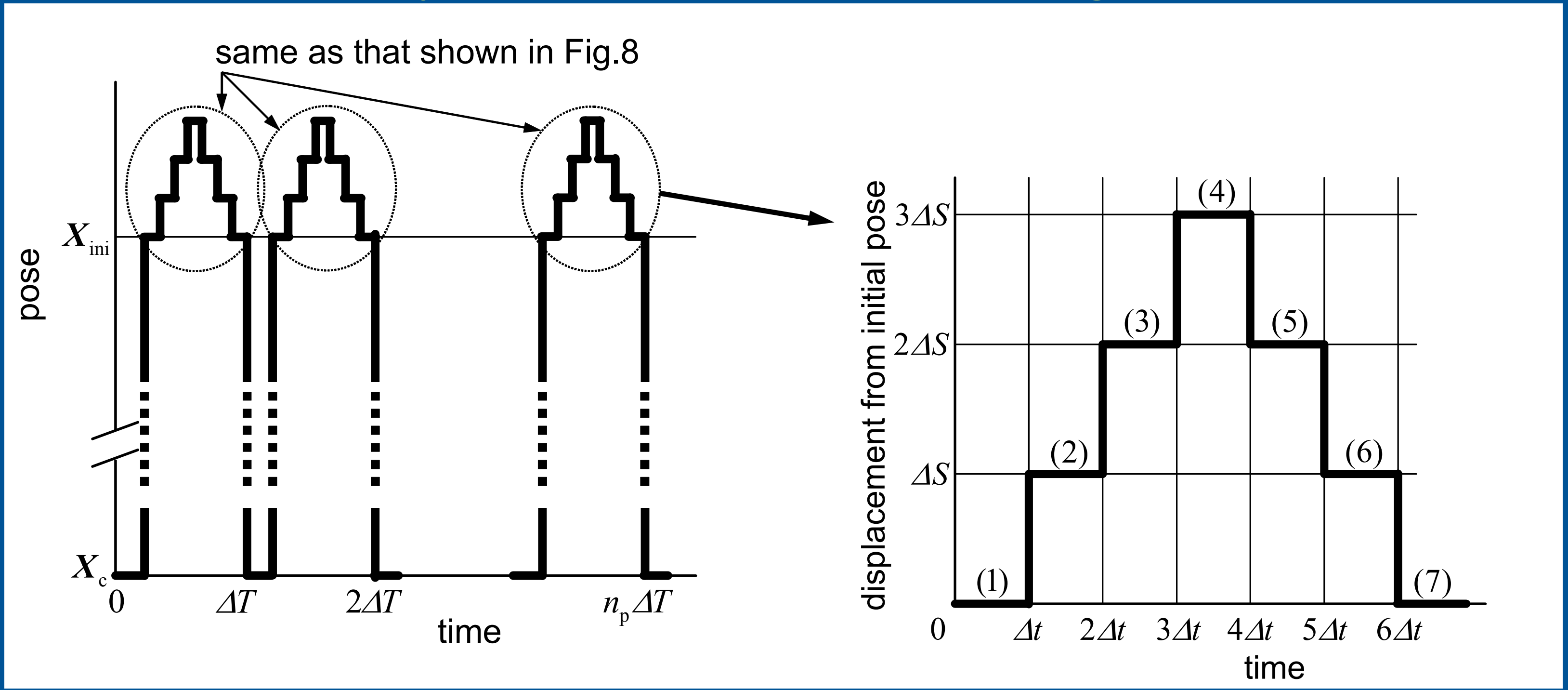
(4) X direction, rotation, at (0,0,Zc) mm

Summary of exp.1 : fine translational and rotational motions were successfully achieved for very fine steps of 20nm and 1μrad in all directions and in the workspace.

Experimental investigations

Tokyo Institute of Technology
Mechanical Systems Design Lab.

Exp.2 :Successive fine step motion followed by a large displacement was given as the desired motion to investigate position repeatability in the motion with a large displacement



Change of desired pose

Fine step motion

Experimental results:

Repeatability : 3～6nm for 20～40 mm gross motion displacement and 50nm fine motion successive steps

Conclusions-redundant actuators

A redundant parallel manipulator with actuators for gross and fine motions was developed. Its control system was constructed and fine motion characteristics were experimentally investigated.

- A control system to achieve a fine motion together with a gross motion and a procedure to determine input displacement of gross and fine motion drive systems for a specified pose of the output link were presented.
- The positioning resolutions of our prototype manipulator were found to be 20 nm in the working space of 80 x 80 x 40 mm.
- Position repeatability in fine positioning followed by a large displacement was also found to be better than 6 nm for a 20 or 40 mm displacement.

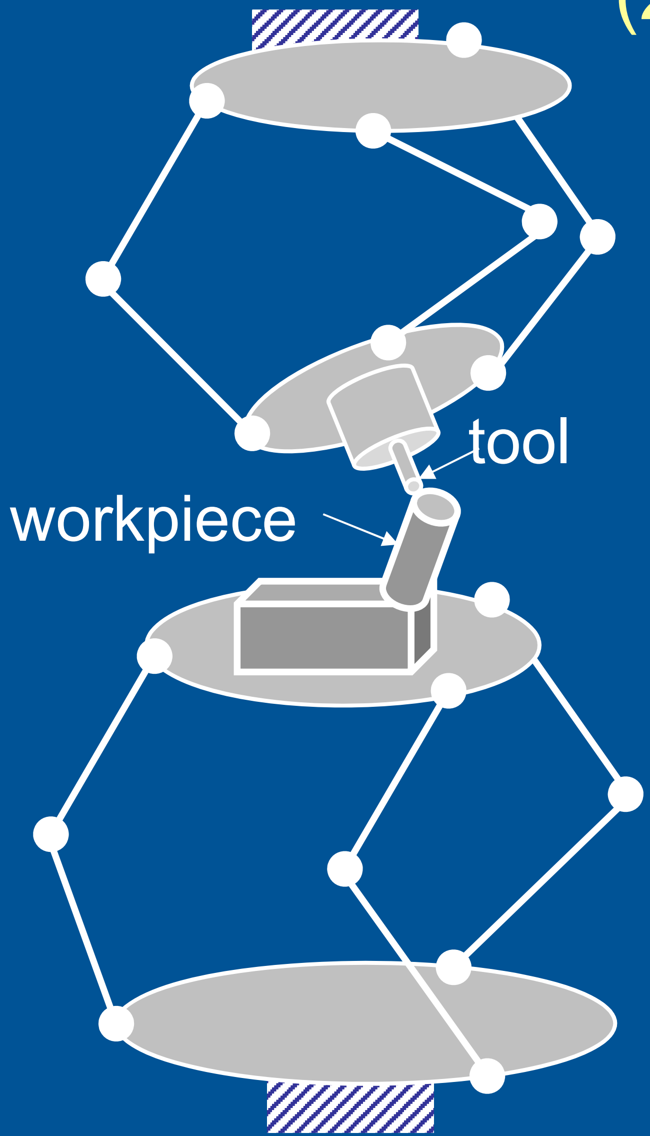
According to these results, a high ratio greater than 10^6 of total stroke of gross motion to positioning resolution and repeatability was achieved by a parallel manipulator with redundant actuators for gross and fine motions.

Limited-dof Mechanism

Development of hybrid manipulator

Tokyo Institute of Technology
Mechanical Systems Design Lab.

(2006～)



Pure-rotational mechanism

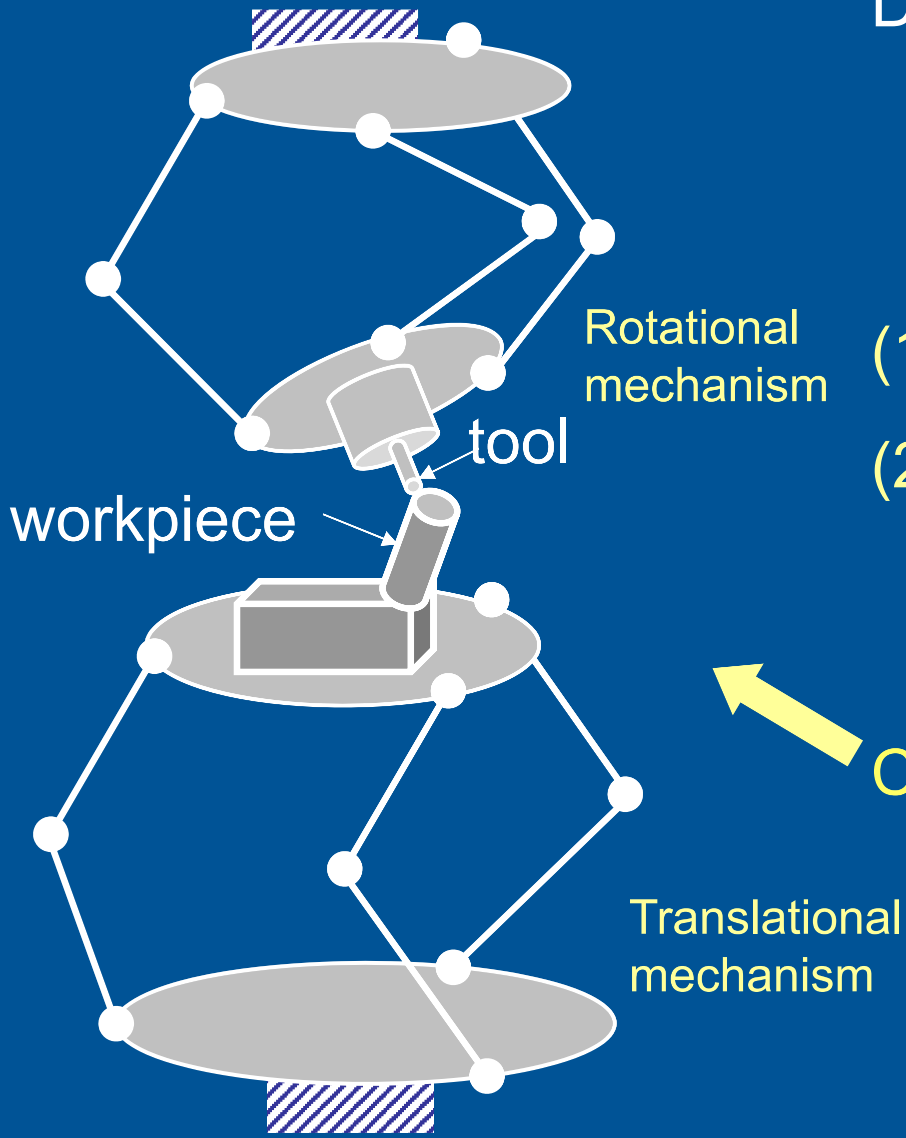
- 3-URU parallel mechanism

- Kinematic analysis and synthesis
- Error and stiffness analyses
- Calibration and compensation

Pure-translational mechanism

- 3-5R or 3-RUU parallel mechanism

Workspace



Drawbacks of 6-dof mechanism such as Stewart-Gough platform with respect to workspace :

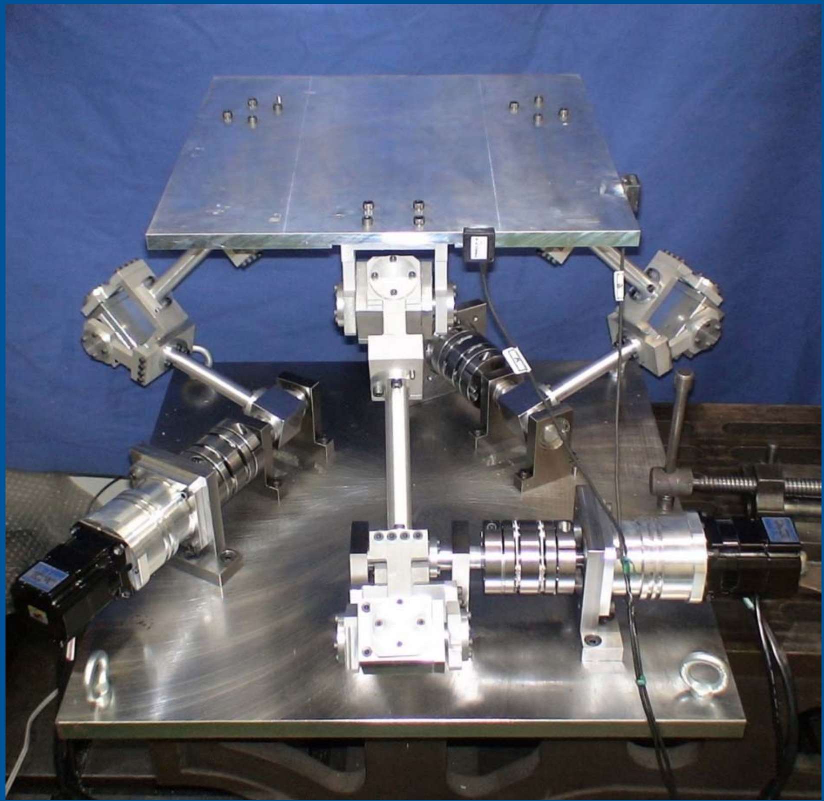
(1)Small orientation workspace

(2)Dependence of the orientation workspace on the position.

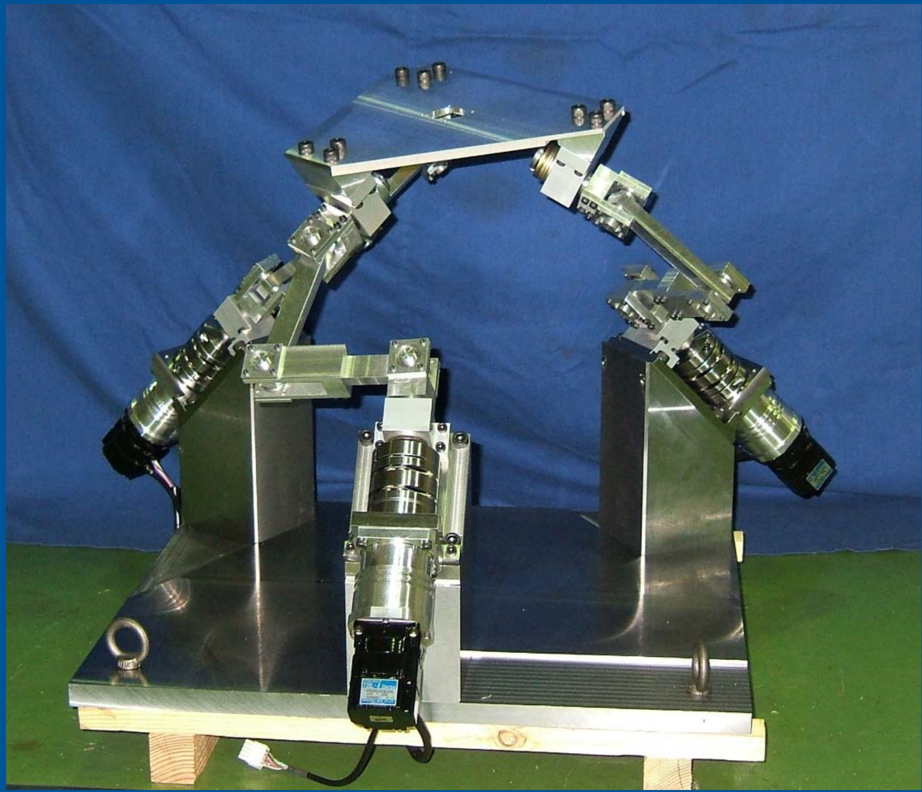
Considering such an application, rotational mechanism should have a large orientation workspace to have advantage compared with 6-dof mechanism.

Prototypes(2007.8)

Tokyo Institute of Technology
Mechanical Systems Design Lab.



3-RUU pure translational
parallel mechanism



3-URU pure rotational
parallel mechanism

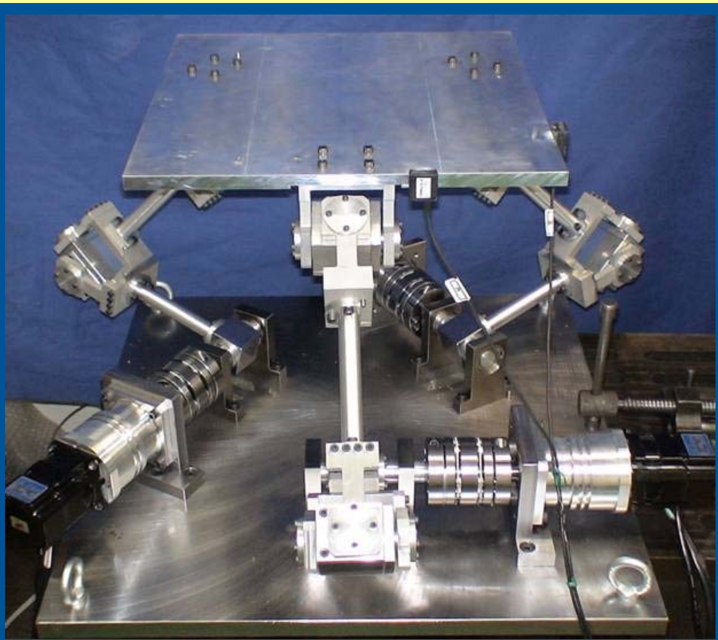
Accuracy/Error

Tokyo Institute of Technology
Mechanical Systems Design Lab.

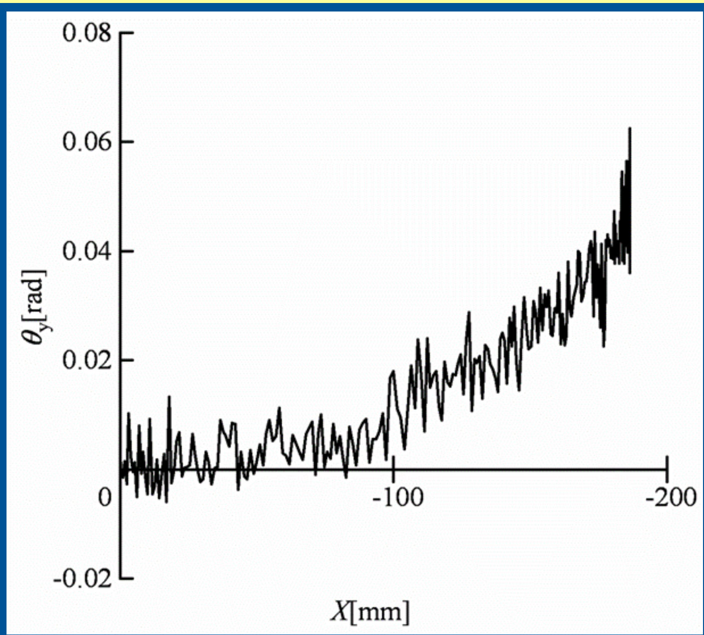
	Output displacement error	Compensation (by calibration, feedback control)
6-dof mechanisms	6-dimension	Compensatable
3-dof spatial mechanisms	6-dimension	Partially (3 comp.) compensatable Partially (3 comp.) uncompensatable

These components should be considered in the mechanism design in order to achieve precise motion.

Introduction (motivation)



Prototype of TPM (2007) (video)



Change of platform orientation

Types of output pose error of a manipulator (caused by dimensional errors)

Compensatable error : it can be compensated for by calibration or full closed-loop control.

Uncompensatable error : it cannot be compensated for by any means.
typical error in lower-dof manipulators.

Ex. Orientation error of the platform of a translational parallel manipulator

Introduction (purpose)

Approaches to the uncompensatable error in limited(lower)-dof parallel mechanism :

1. To minimize uncompensatable error by determining the optimal values of kinematic constants at the design stage (Huda, Takeda, 2008), taking tolerances into account.
2. To change the structure of the mechanism so that fine adjustments can be added to the output motion to eliminate the uncompensatable error.

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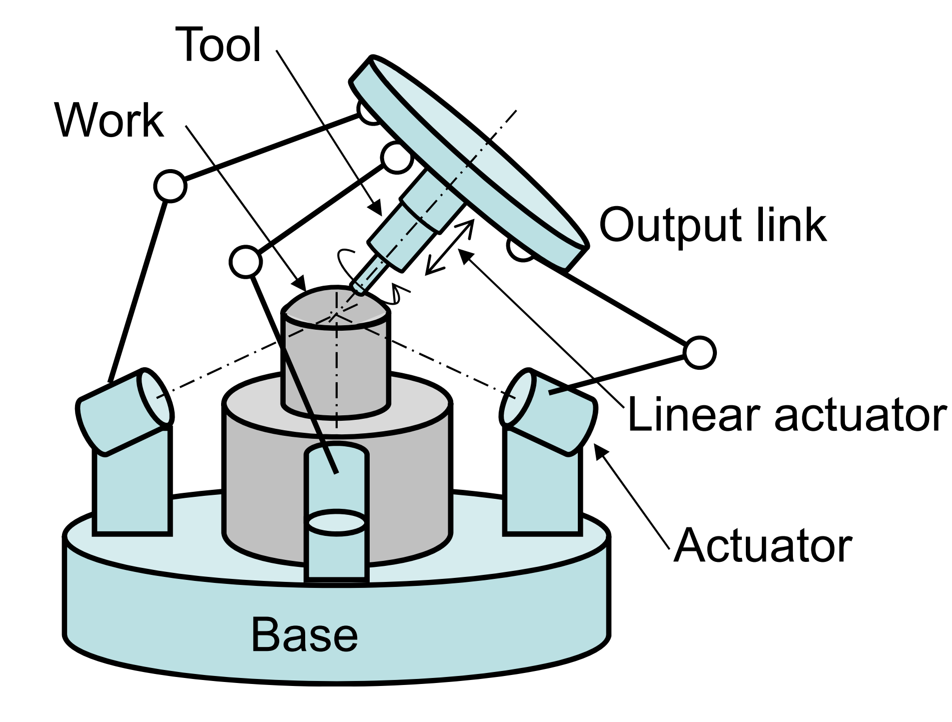
Target Application



Machine tool application of a pure rotational parallel mechanism

There are more applications of pure rotational and pure translational parallel mechanisms.

Requirements:

1. High Accuracy
2. Large Workspace
3. Etc.

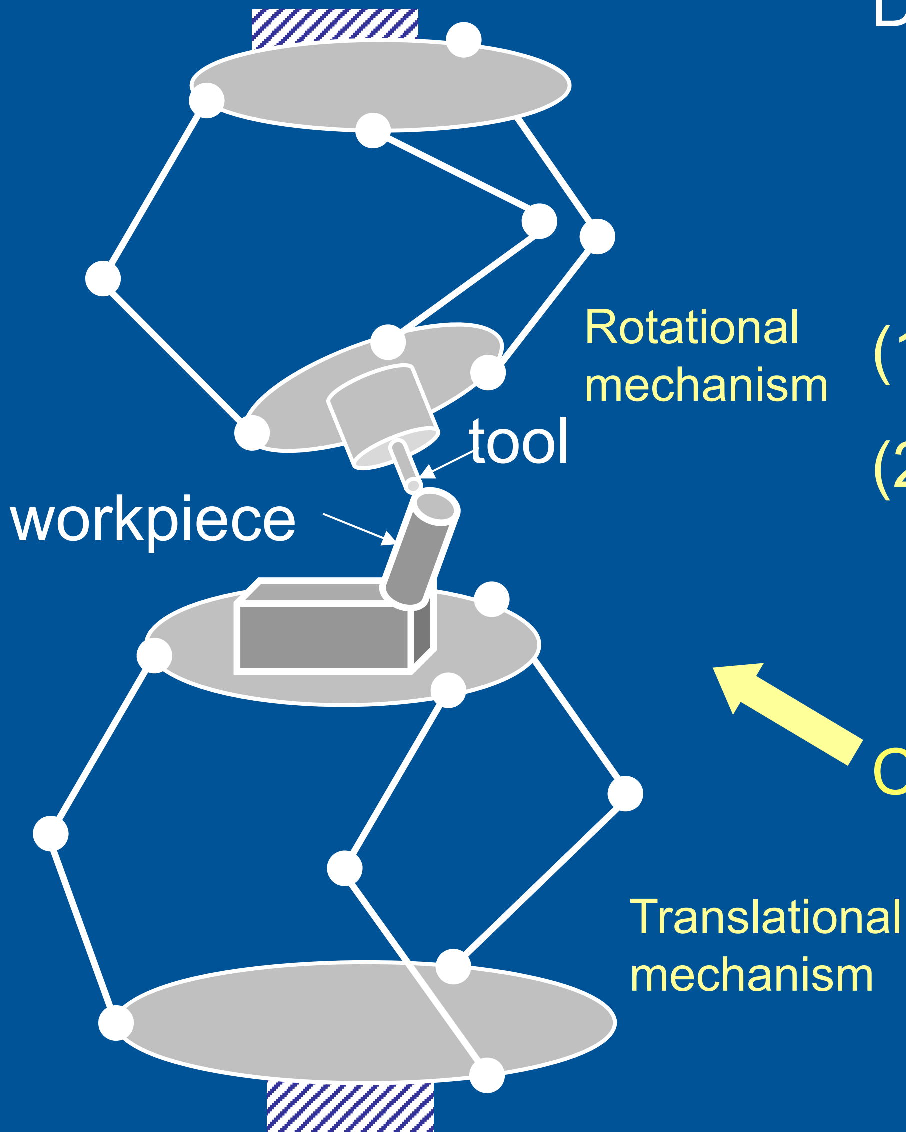
This presentation is focused on the pure rotational parallel mechanism.

Introduction (purpose)

Approach to the uncompensatable error :

1. To minimize uncompensatable error by determining the optimal values of kinematic constants at the design stage (Huda, Takeda, 2008), taking tolerances into account.
2. To change the structure of the mechanism so that fine adjustments can be added to the output motion to eliminate the uncompensatable error.

Workspace



Drawbacks of 6-dof mechanism such as Stewart-Gough platform with respect to workspace :

(1)Small orientation workspace

(2)Dependence of the orientation workspace on the position.

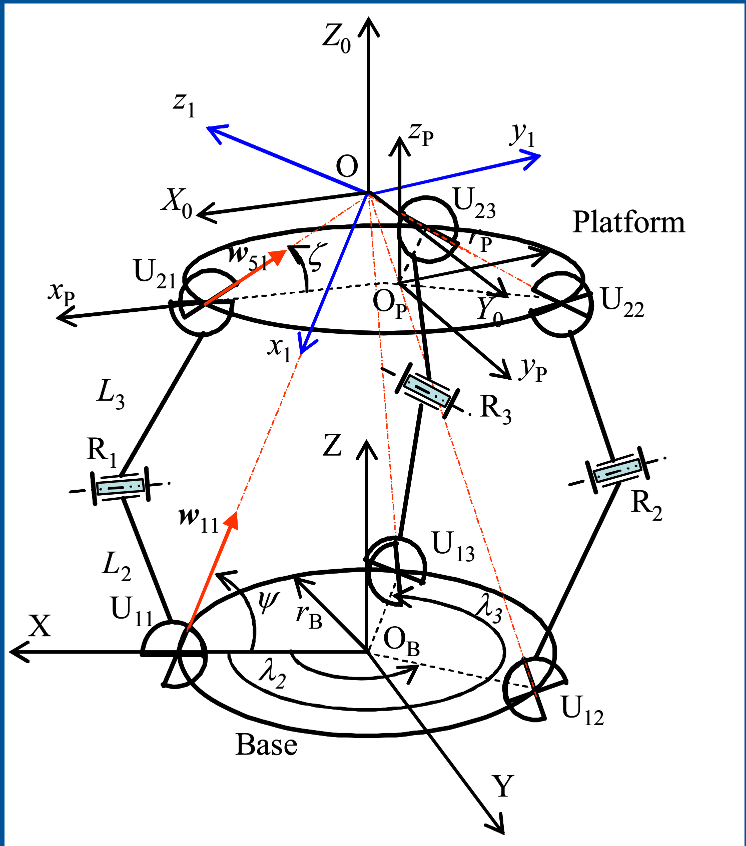
Considering such an application, rotational mechanism should have a large orientation workspace to have advantage compared with 6-dof mechanism.

Purpose of the present work and composition of the presentation

Purpose : to design a pure rotational parallel mechanism performing precise motion within a large workspace. (3-URU structure is considered)

Table of contents:

Mechanism configuration (3-URU mechanism)



3-URU pure rotational parallel mechanism (a special case of 3-5R parallel mechanism)

Condition for pure rotational motion:

1. The first and fifth axes of each chain meet at the point, which is the center of rotation of the platform.
2. The 2nd, 3rd and 4th joint axes of each chain are parallel.

Kinematic constants:

r_B, r_P : location radii of the universal joints on the base and the platform

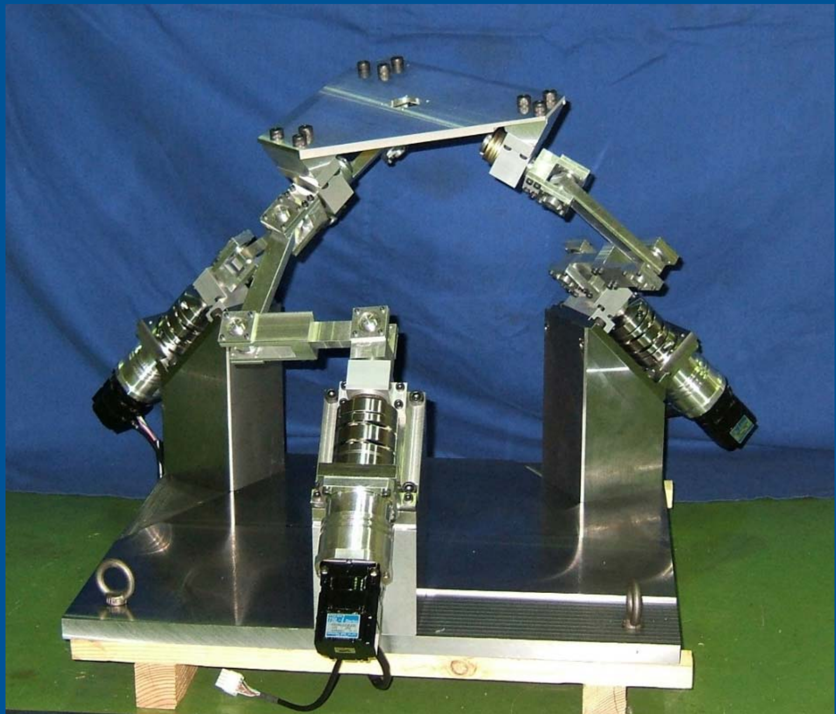
ψ : angle of the first joint axis from the base plane

ζ : angle of the fifth joint axis from the platform plane

L_2, L_3 : link lengths

These are determined in the design while the above conditions are satisfied.

Mechanism configuration (3-URU mechanism)



1st prototype of 3-URU pure rotational parallel mechanism (a special case of 3-5R parallel mechanism)

Condition for pure rotational motion:

1. The first and fifth axes of each chain meet at the point, which is the center of rotation of the platform.
2. The 2nd, 3rd and 4th joint axes of each chain are parallel.

Kinematic constants:

r_B, r_P : location radii of the universal joints on the base and the platform

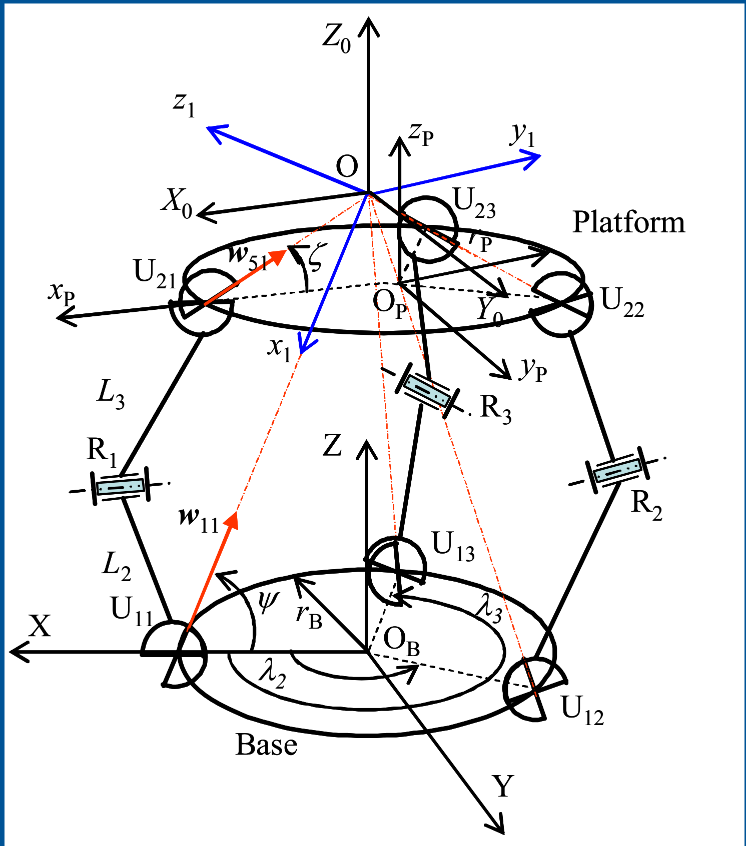
ψ : angle of the first joint axis from the base plane

ζ : angle of the fifth joint axis from the platform plane

L_2, L_3 : link lengths

These are determined in the design while the above conditions are satisfied.

Basic design flow (singularity and workspace)



3-URU mechanism

Condition for basic design:

(1) The reachable workspace by the mechanism should include the prescribed workspace.

(2) There are no singular points in the prescribed workspace.

Basic design flow (Huda and Takeda,2007):

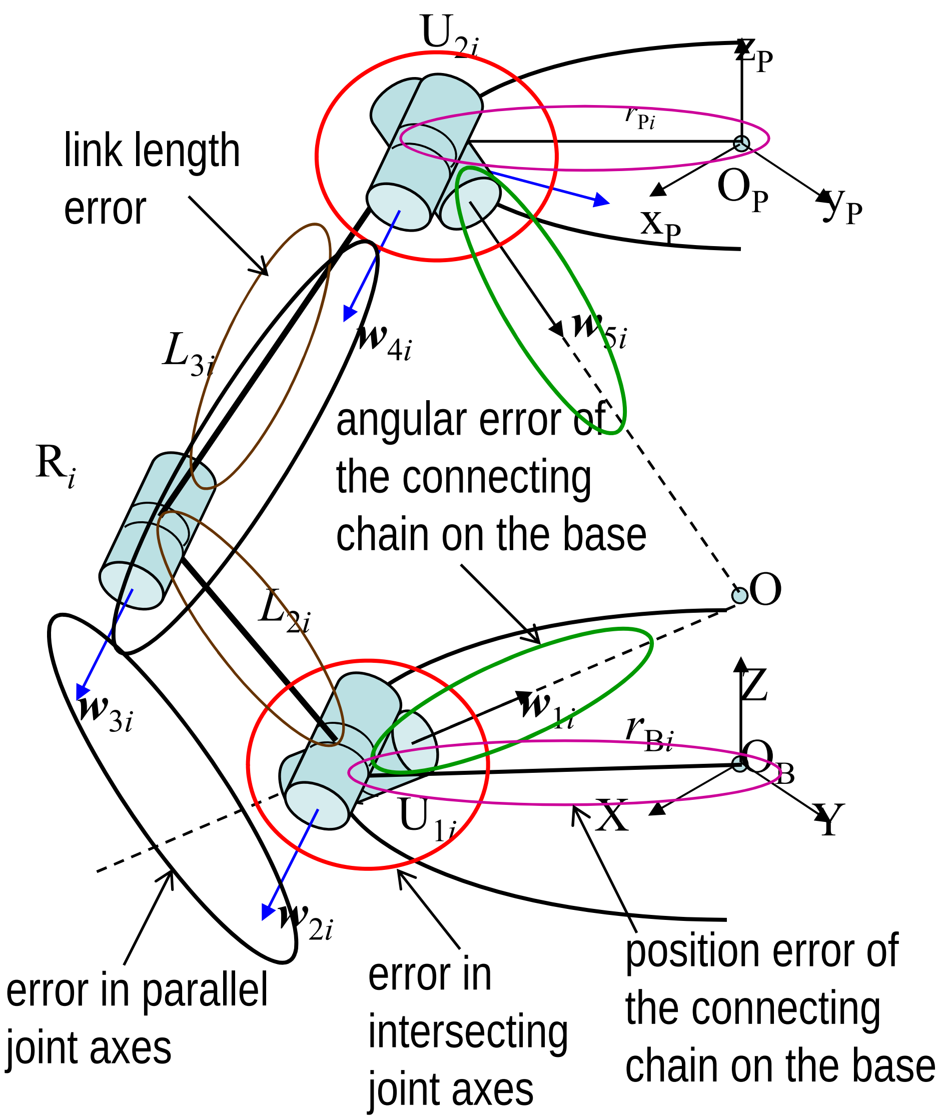
(1) Evaluation of kinematic constants ψ, ζ, r_B and r_P based on singularity conditions.

(2) Evaluation of kinematic constants other than ψ, ζ, r_B and r_P taking account of the reachable workspace.

(3) Optimization and determination of kinematic constants using a performance index.

As the performance index, we use the uncompensatable error index in this work.

Error model

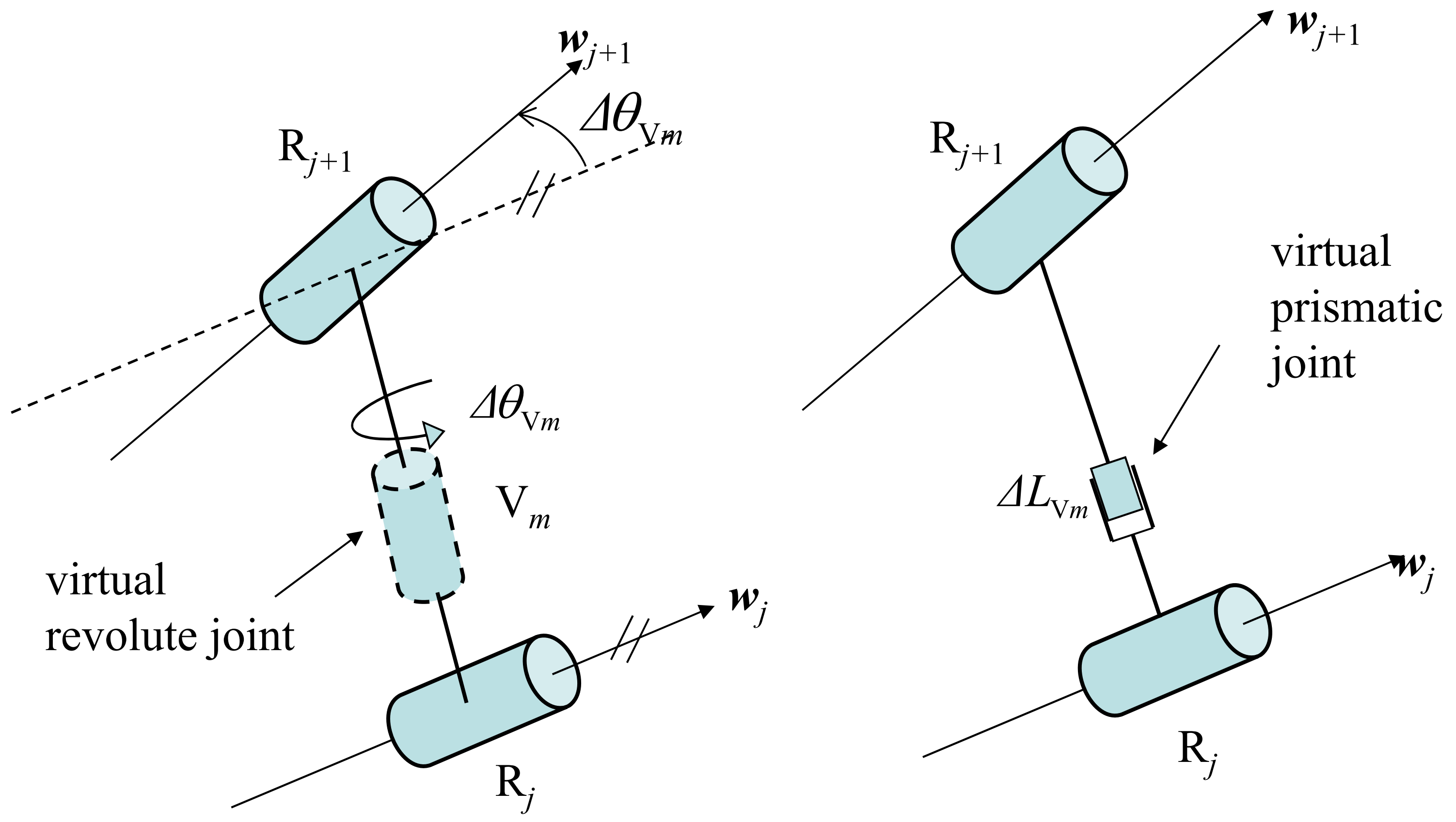


Location of error sources

Types of error:

- Errors in parallel axes between R_2 and R_3 and between R_3 and R_4.
- Errors in intersecting axes between R_1 and R_2 and between R_4 and R_5.
- Angular errors of the universal joints on the base and platform.
- Position errors of the universal joints on the base and platform.

Introduction of a virtual joint to represent a kinematic error



Model of angular error

Model of linear error

Sensitivity formulation and the Uncompensatable error

Sensitivity equation for l error sources:

$$\Delta \boldsymbol{X}_{\text{total}} = \sum_{m=1}^{l} \Delta \boldsymbol{X}_m = \sum_{m=1}^{l} \left(J_{\text{x}m} \right)^{-1} J_{\text{q}m} \Delta \boldsymbol{q}_m = \sum_{m=1}^{l} S_m \Delta \boldsymbol{q}_m$$

$$\begin{bmatrix} \Delta\Theta_{\text{X}} \\ \Delta\Theta_{\text{Y}} \\ \Delta\Theta_{\text{Z}} \\ \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} (3\times 3) \\ S_{\text{T}m}(3\times 3) \end{bmatrix} \begin{bmatrix} \Delta\theta_{\text{V}m1} \\ \Delta\theta_{\text{V}m2} \\ \Delta\theta_{\text{V}m3} \end{bmatrix}$$

Orientation part

(for m-th error source)

Position part

This matrix can be obtained by the reciprocal screw theory.

Uncompensatable error of a pure rotational parallel mechanism:

Position part of the above equation is related to the uncompensatable error. This means the position error of the center of rotation of the platform cannot be compensated by calibration nor closed-loop control.

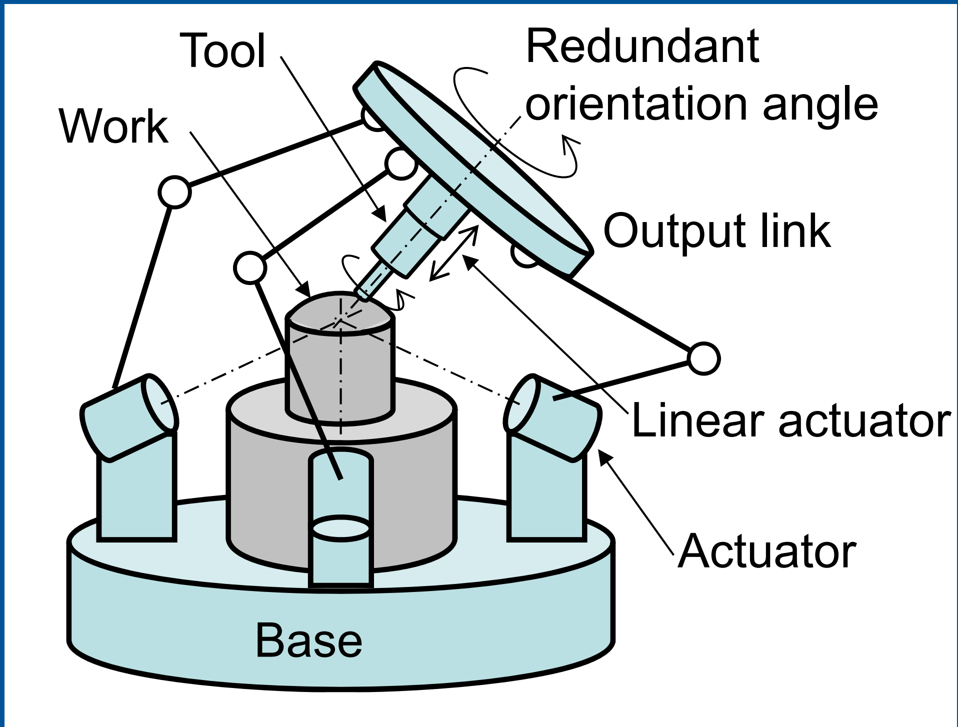
Sensitivity formulation and the Uncompensatable error index

Uncompensatable error index:

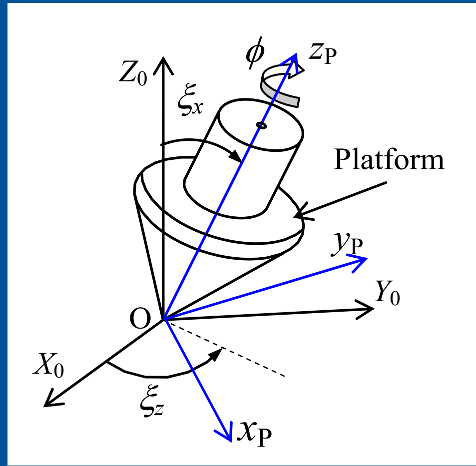
$\Delta E_{\max}$ is the maximum position error taking all error sources into consideration under the following condition. Δq_m is determined based on the manufacturing tolerance.

$$\Delta \boldsymbol{x}_m = S_{\mathrm{T}m} \Delta \boldsymbol{q}_m \qquad \begin{bmatrix} -1 \\ -1 \\ -1 \end{bmatrix} \Delta q_m \le \Delta \boldsymbol{q}_m \le \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \Delta q_m$$

Optimal design



Machine tool application of a pure rotational parallel mechanism



Orientation angles of the platform

In this application, two angles (ξ_x, ξ_z) are necessary to control. The resultant angle ϕ is considered redundant. This redundant orientation is optimized to minimize the uncompensatable error for each set (ξ_x, ξ_z).

Design specifications:

- orientation workspace

$$\left.\begin{array}{l} 0 \le \xi_x \le \xi_{x(\max)} \\ 0 \le \xi_z \le 2\pi \end{array}\right\}$$

- position of the center of rotation relative to the platform ζ

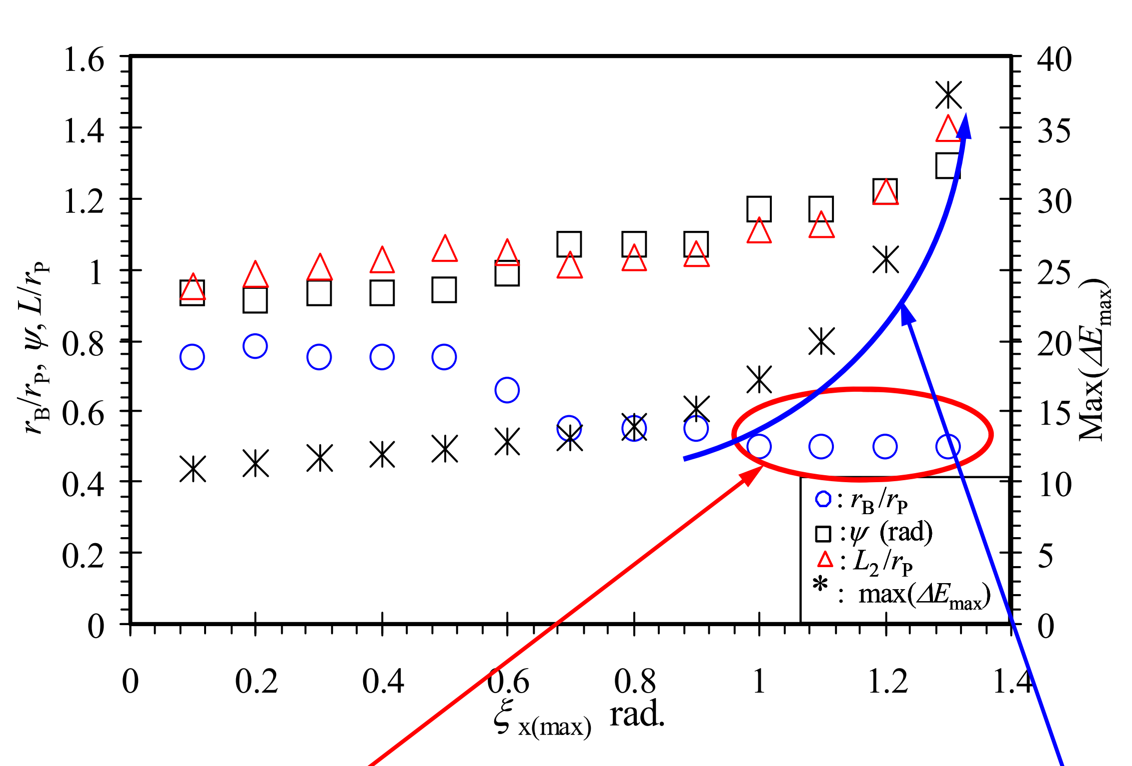
Optimal design

Optimal design was carried out to reveal the characteristics of the 3-URU mechanism. The results were summarized by design charts to represent the following relationships.

1. The relationship between the maximum inclination angle and the optimal kinematic constants, while the position of the center of rotation is kept constant.
2. The relationship between the position of the center of rotation and the optimal kinematic constants, while the maximum inclination angle is kept constant.

*In this optimal design, the optimization process of the redundant orientation angle ϕ is included.

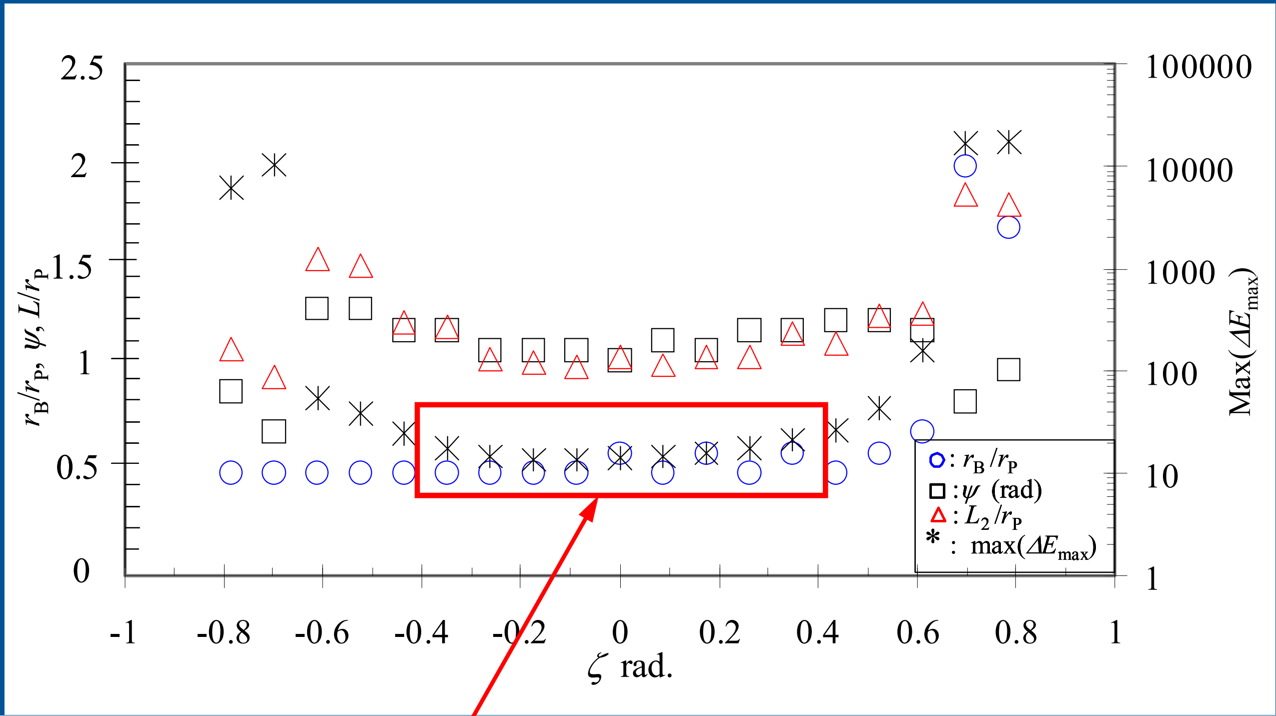
Optimal design result(1)



Relationship between $\xi_{x(max)}$ and the optimal kinematic constants and Max(ΔE_{max}) at ζ =0

It is known from the figure that for a large inclination angle such as $\xi_{x(max)} > 1$ rad, smaller base radius relative to the platform results in lower sensitivity with respect to uncompensatable error. Moreover, Max(ΔE_{max}) increases with the maximum inclination angle.

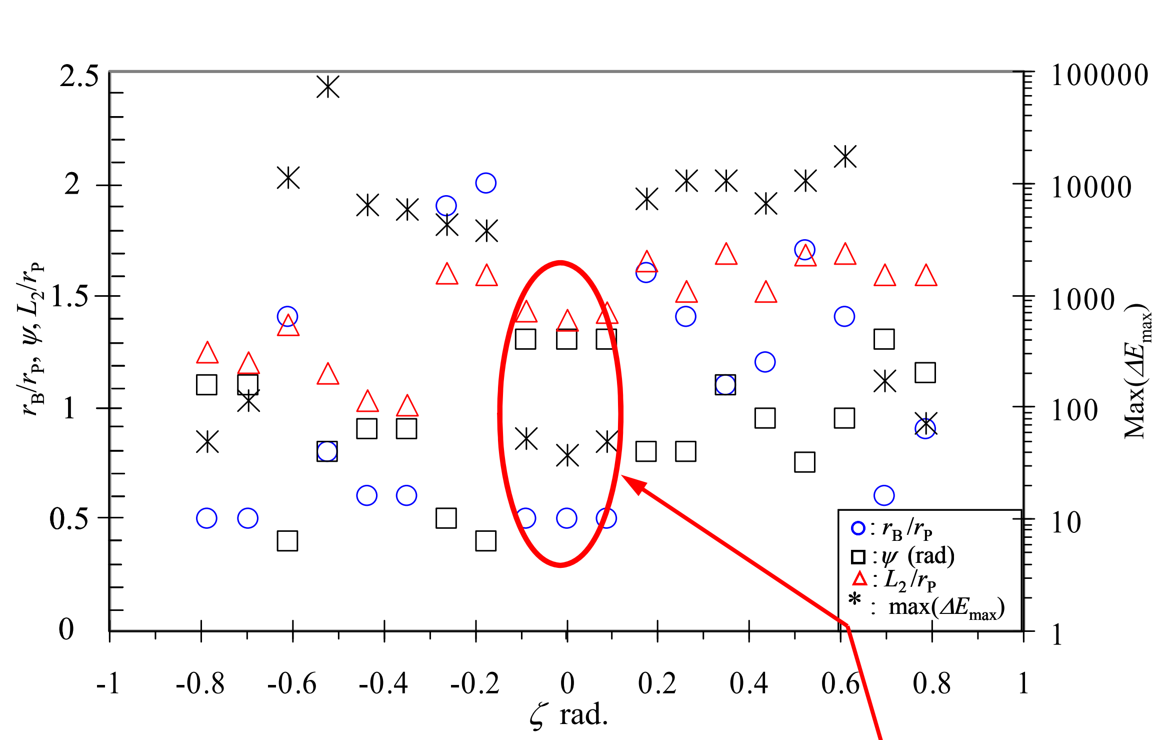
Optimal design result(2-a)



(a) $\xi_{x(max)}$=0.6rad
Relationship between ζ and optimal kinematic constants and Max(ΔE_{max})

It is known from the figure that for smaller inclination angle there are some ranges of ζ by which the uncompensatable error is kept within a small range($-0.4 \le \zeta \le 0.4$ rad) .

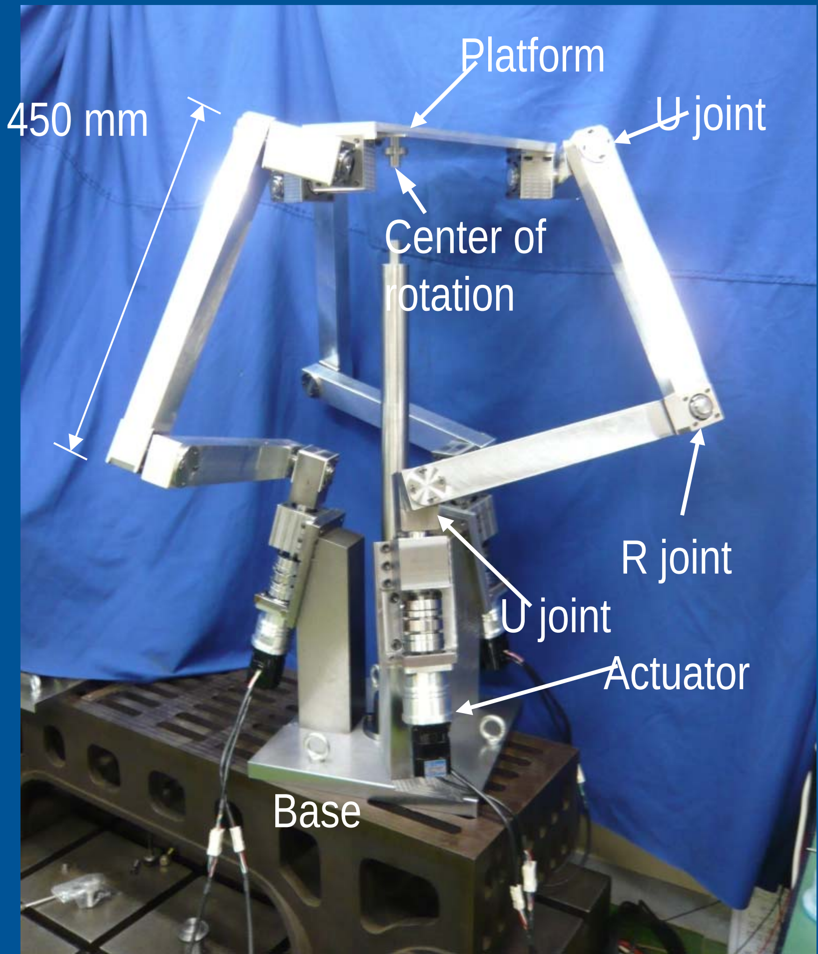
Optimal design result(2-b)



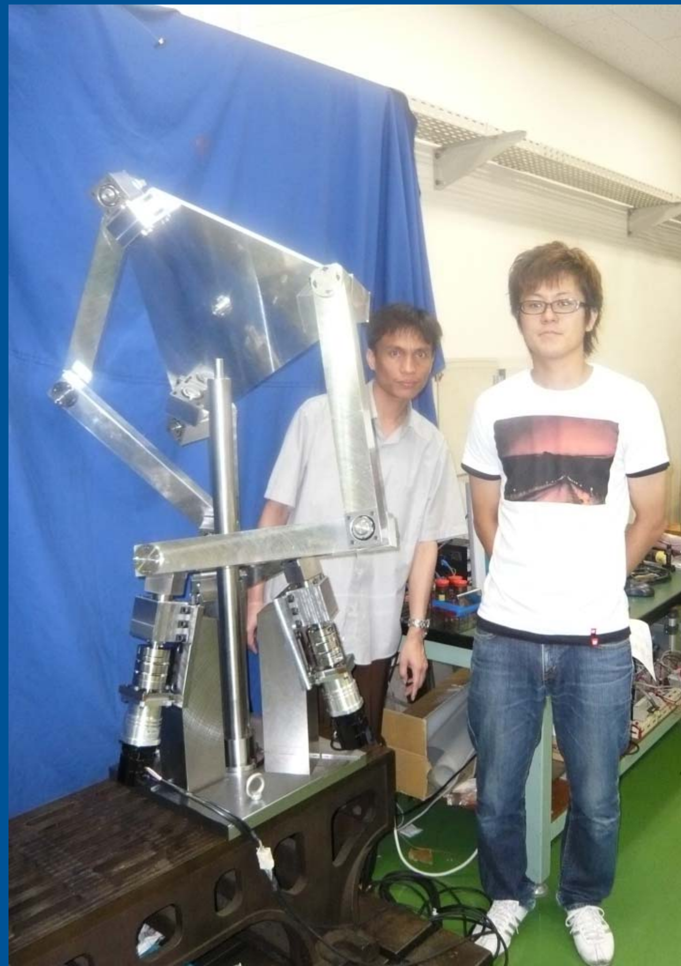
(b) $\xi_{x(max)}$=1.3rad
Relationship between ζ and optimal kinematic constants and Max(ΔE_{max})

It is known from the figure that there are few range of ζ that give small uncompensatable error for a larger inclination angle. It is also found that the best choice for this case is expected to be ζ=0.

Prototype



Overview of the prototype



Configuration at $\xi_x = 65^\circ$
(with the co-authors)

Conclusions-optimal design for low sensitivity

In the present paper, we carried out a kinematic design of 3-URU pure rotational parallel mechanism with a large workspace subject to minimization of the position error of the center of platform rotation.

(1) Optimal kinematic constants and the magnitude of the position error of the center of platform rotation for the design specification in the maximum inclination angle of the platform have been clarified. The result was summarized in some charts that are useful in kinematic design.

(2) Using the charts, it was found that the center of platform rotation should be located on the platform plane for a large maximum inclination angle. On the other hand, the center of platform rotation can be specified within some range considering the application of the mechanism for a small maximum inclination angle.

(3) An optimal design result and a prototype was shown for an orientating device of a machine tool which can achieve a large maximum inclination angle such as 1.3 rad based on the results mentioned above.

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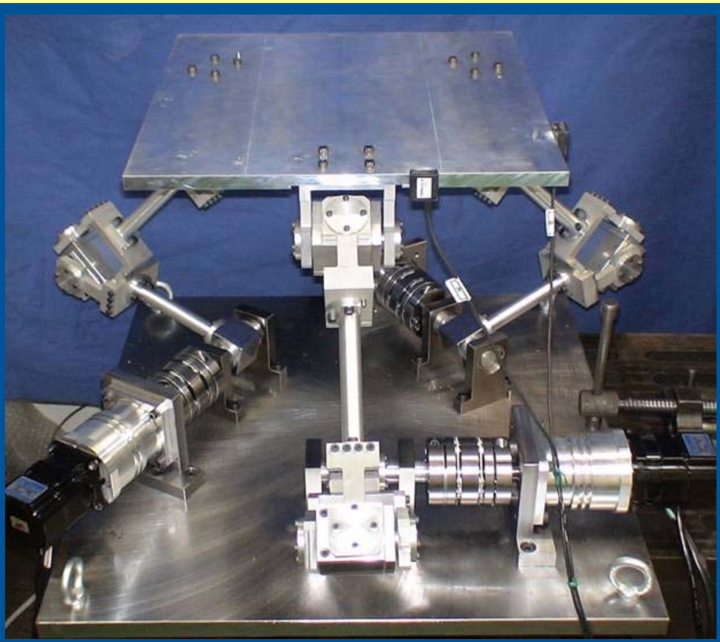
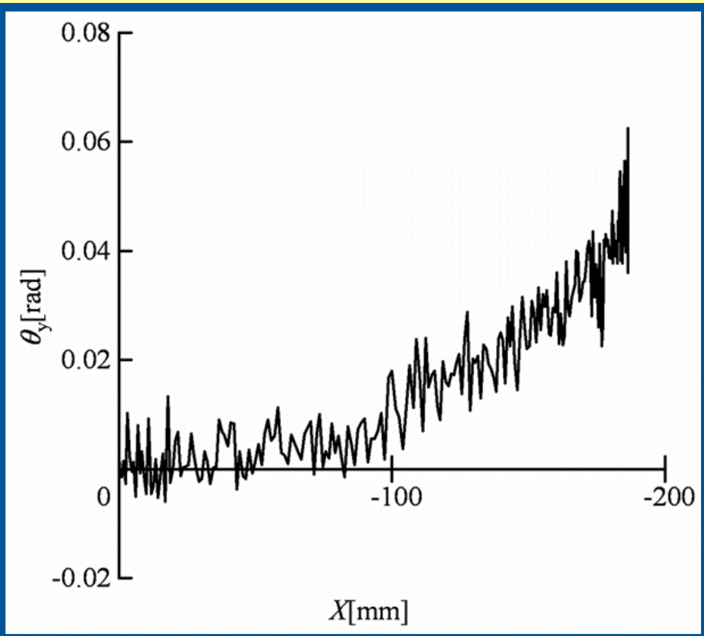
Mechanical Systems Design Lab.

Introduction (motivation)



Prototype (2007)
(video)



Change of platform orientation

Types of output pose error of a manipulator (caused by dimensional errors)

Compensatable error : it can be compensated for by calibration or full closed-loop control.

Uncompensatable error : it cannot be compensated for by any means.
typical error in lower-dof manipulators.

Ex. Orientation error of the platform in a translational parallel manipulator

Introduction (purpose)

Approach to the uncompensatable error :

1. To minimize uncompensatable error by determining the optimal values of kinematic constants at the design stage (Huda, Takeda, 2008), taking tolerances into account.
2. To change the structure of the mechanism so that fine adjustments can be added to the output motion to eliminate the uncompensatable error.

The present paper discusses the kinematic design of a translational parallel manipulator with fine adjustment capability of platform orientation (TPMFAO).

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Basic concept for structural synthesis of TPMFAO

Target manipulator : A manipulator must have six degrees of freedom to achieve fine adjustments of the platform orientation with gross translational motion.

Key point : output motion = main (translation) + sub (rotation)
each with 3 dof

Conditions considered in the structural synthesis:

(1) It has three connecting chains.

(2) Each connecting chain has the same structure.

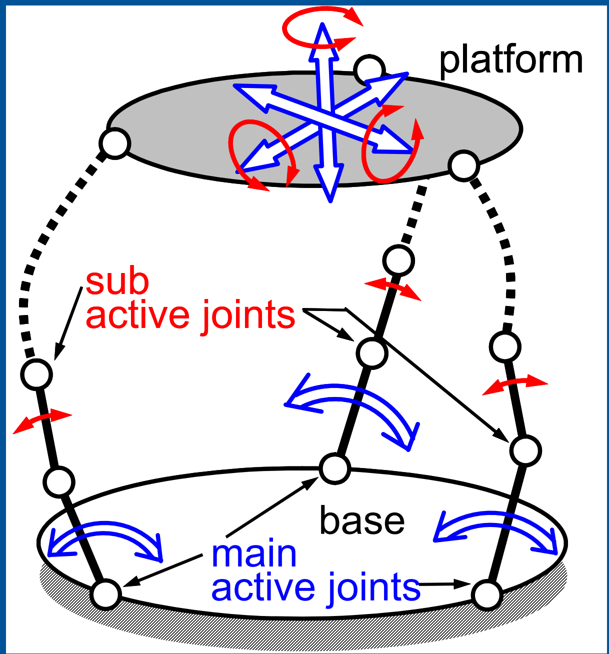
(3) Revolute and prismatic joints are used to compose a connecting chain.

(4) Each connecting chain has two active joints. One active joint is to correspond to the translational output motion, and is called a main active joint. The other is used to make fine adjustment to the platform's orientation, and is a sub-active joints.

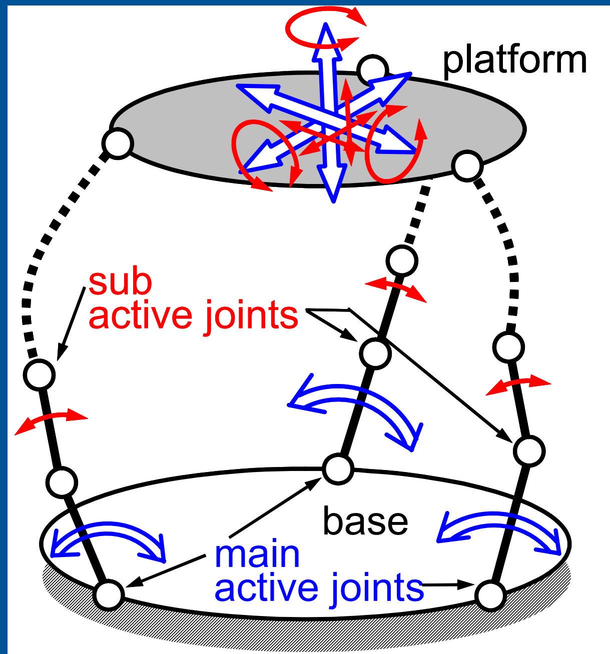
(5) The main active joints are located at the first or second joints, while any location for the sub-active joints is accepted.

Candidates for TPMFAO

Fully-decoupled mechanism



Partially-decoupled mechanism



Input-output infinitesimal displacement relationships:

$$\begin{bmatrix} \Delta\boldsymbol{\Theta} \\ \Delta\boldsymbol{X} \end{bmatrix} = J_{\mathrm{FD}} \begin{bmatrix} \Delta\boldsymbol{q}_{\mathrm{M}} \\ \Delta\boldsymbol{q}_{\mathrm{S}} \end{bmatrix}$$

$$J_{\mathrm{FD}} = \begin{bmatrix} 0_3 & B_{\mathrm{FD}} \\ A_{\mathrm{FD}} & 0_3 \end{bmatrix}$$

$$\begin{bmatrix} \Delta\boldsymbol{\Theta} \\ \Delta\boldsymbol{X} \end{bmatrix} = J_{\mathrm{PD}} \begin{bmatrix} \Delta\boldsymbol{q}_{\mathrm{M}} \\ \Delta\boldsymbol{q}_{\mathrm{S}} \end{bmatrix}$$

$$J_{\mathrm{PD}} = \begin{bmatrix} 0_3 & B_{\mathrm{PD}} \\ A_{\mathrm{PD}} & C_{\mathrm{PD}} \end{bmatrix}$$

Fully-decoupled mechanism for TPMFAO (Synthesis conditions)

Conditions for chain:

Each connecting chain should become

(1) a chain for a translational parallel mechanism when the sub-active joints are locked at any position, and

(2) a chain for a pure rotational parallel mechanism when the main active joints are locked at any position.

Conditions for joint :

(1) Conditions for generating translational motion

i. The axis directions of revolute joints are two.

ii. There are fewer than four prismatic joints.

(2) Conditions for generating pure rotational motion

i. There are more than one revolute joint belonging to the first group.

ii. Prismatic joints are perpendicular to the revolute joints belonging to the second group.

iii. There are fewer than three prismatic joints.

Fully-decoupled mechanism for TPMFAO (Synthesis results)

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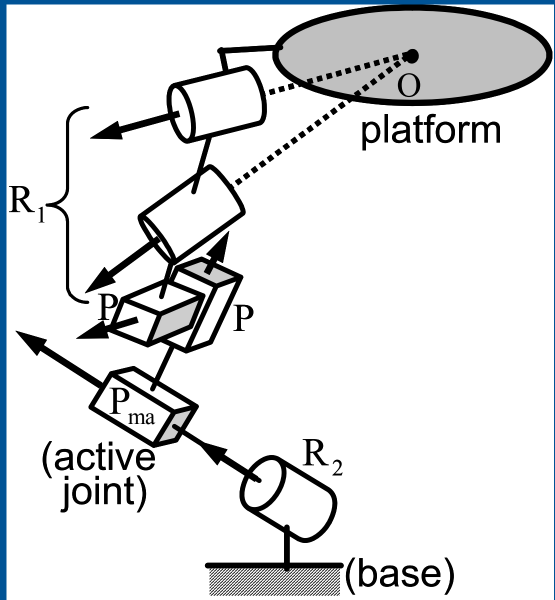
Classes	Types of connecting chains					
5R1P	$\dot{P}_{ma}R_2R_2R_2R_{1sa}R_1$	$R_2\dot{P}_{ma}R_2R_2R_{1sa}R_1$	$\dot{P}_{ma}R_2R_2R_2R_1R_{1sa}$	$R_2\dot{P}_{ma}R_2R_2R_1R_{1sa}$		
4R2P	$\dot{P}_{ma}\bar{P}R_2R_2R_{1sa}R_1$	$\bar{P}\dot{P}_{ma}R_2R_2R_{1sa}R_1$	$\dot{P}_{ma}R_2\bar{P}R_2R_{1sa}R_1$	$R_2\dot{P}_{ma}\bar{P}R_2R_{1sa}R_1$	$\dot{P}_{ma}R_2R_2\bar{P}R_{1sa}R_1$	$R_2\dot{P}_{ma}R_2\bar{P}R_{1sa}R_1$
	$\dot{P}_{ma}\bar{P}R_2R_2R_1R_{1sa}$	$\bar{P}\dot{P}_{ma}R_2R_2R_1R_{1sa}$	$\dot{P}_{ma}R_2\bar{P}R_2R_1R_{1sa}$	$R_2\dot{P}_{ma}\bar{P}R_2R_1R_{1sa}$	$\dot{P}_{ma}R_2R_2\bar{P}R_1R_{1sa}$	$R_2\dot{P}_{ma}R_2\bar{P}R_1R_{1sa}$
3R3P	$\dot{P}_{ma}\bar{P}\tilde{P}R_2R_1R_1$	$\bar{P}\dot{P}_{ma}\tilde{P}R_2R_1R_1$	$\dot{P}_{ma}\bar{P}R_2\tilde{P}R_1R_1$	$\bar{P}\dot{P}_{ma}R_2\tilde{P}R_1R_1$	$\dot{P}_{ma}R_2\bar{P}\tilde{P}R_1R_1$	$R_2\dot{P}_{ma}\bar{P}\tilde{P}R_1R_1$
	$PPPR_1R_1R_1$					

(Subscript “ma” means that it must be a main active joint.)



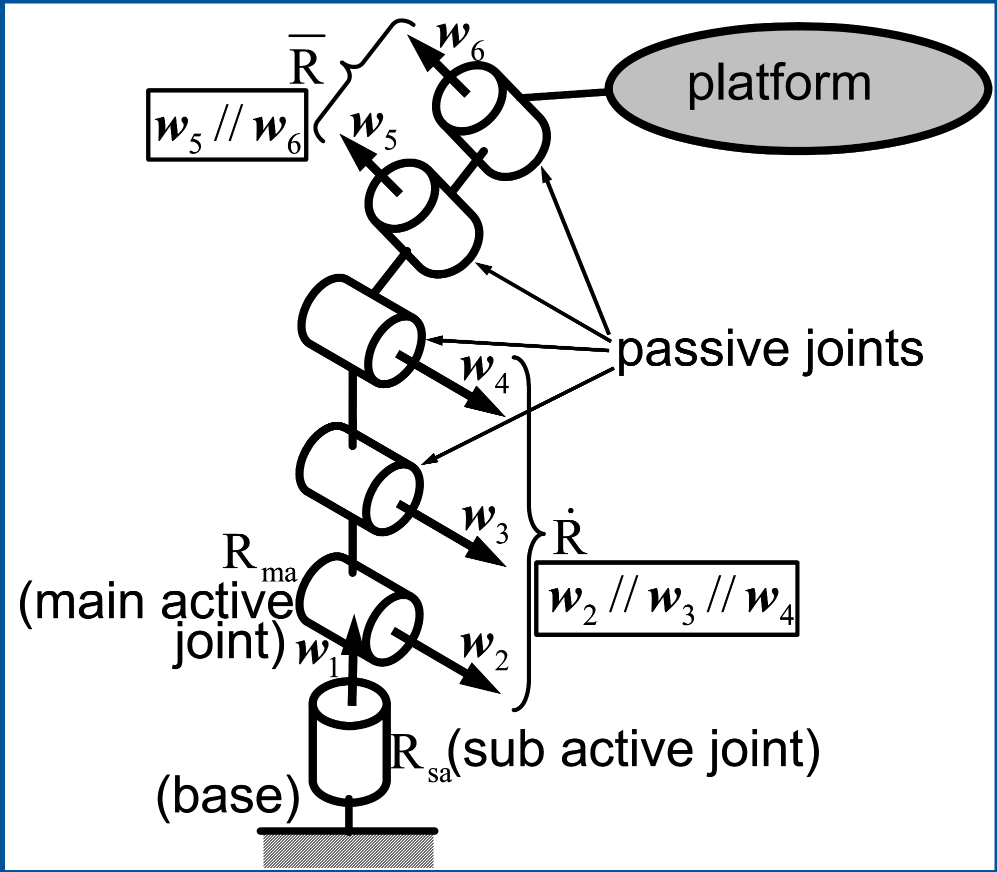
$R_2\dot{P}_{ma}\bar{P}\tilde{P}R_1R_1$ connecting chain
for full-decoupled mechanism

Partially-decoupled mechanism for TPMFAO (Synthesis results)

Classes	Types of connecting chains							
6R	$R_{sa}\dot{R}\dot{R}\dot{R}\overline{RR}$	$\dot{R}\dot{R}\dot{R}R_{sa}\overline{RR}$	$\dot{R}\dot{R}\dot{R}\overline{RR}R_{sa}$					
5R1P	$R_{sa}\dot{R}\dot{R}\overline{RR}P$	$\dot{R}\dot{R}R_{sa}\overline{RR}P$	$\dot{R}\dot{R}\overline{RR}R_{sa}P$	$\dot{R}\dot{R}\overline{RR}PR_{sa}$	$\dot{R}\dot{R}R_{sa}\overline{R}P\overline{R}$	$\dot{R}\dot{R}\overline{R}P\overline{R}R_{sa}$	$R_{sa}\dot{R}\dot{R}P\overline{RR}$	$\dot{R}\dot{R}R_{sa}P\overline{RR}$
	$\dot{R}\dot{R}PR_{sa}\overline{RR}$	$\dot{R}\dot{R}P\overline{RR}R_{sa}$	$R_{sa}\dot{R}\dot{R}\dot{R}\overline{R}P$	$\dot{R}\dot{R}\dot{R}R_{sa}\overline{R}P$	$\dot{R}\dot{R}\dot{R}\overline{R}R_{sa}P$	$\dot{R}\dot{R}\dot{R}\overline{R}PR_{sa}$	$R_{sa}\dot{R}\dot{R}\dot{R}P\overline{R}$	$\dot{R}\dot{R}\dot{R}R_{sa}P\overline{R}$
	$\dot{R}\dot{R}\dot{R}PR_{sa}\overline{R}$	$\dot{R}\dot{R}\dot{R}P\overline{R}R_{sa}$	$R_{sa}\dot{R}\dot{R}P\dot{R}\overline{R}$	$\dot{R}\dot{R}P\dot{R}R_{sa}\overline{R}$	$\dot{R}\dot{R}P\dot{R}\overline{R}R_{sa}$	$R_{sa}\dot{R}P\dot{R}\dot{R}\overline{R}$	$\dot{R}P\dot{R}\dot{R}R_{sa}\overline{R}$	$\dot{R}P\dot{R}\dot{R}\overline{R}R_{sa}$
	$R_{sa}P\dot{R}\dot{R}\dot{R}\overline{R}$	$PR_{sa}\dot{R}\dot{R}\dot{R}\overline{R}$	$P\dot{R}\dot{R}\dot{R}R_{sa}\overline{R}$	$P\dot{R}\dot{R}\dot{R}\overline{R}R_{sa}$				
4R2P	$R_{sa}\dot{R}\dot{R}\overline{R}PP$	$\dot{R}\dot{R}R_{sa}\overline{R}PP$	$\dot{R}\dot{R}\overline{R}R_{sa}PP$	$\dot{R}\dot{R}\overline{R}PR_{sa}P$	$\dot{R}\dot{R}\overline{R}PPR_{sa}$	$R_{sa}\dot{R}\dot{R}P\overline{R}P$	$\dot{R}\dot{R}R_{sa}P\overline{R}P$	$\dot{R}\dot{R}PR_{sa}\overline{R}P$
	$\dot{R}\dot{R}P\overline{R}R_{sa}P$	$\dot{R}\dot{R}P\overline{R}PR_{sa}$	$R_{sa}\dot{R}P\dot{R}\overline{R}P$	$\dot{R}P\dot{R}R_{sa}\overline{R}P$	$\dot{R}P\dot{R}\overline{R}R_{sa}P$	$\dot{R}P\dot{R}\overline{R}PR_{sa}$	$R_{sa}P\dot{R}\dot{R}\overline{R}P$	$PR_{sa}\dot{R}\dot{R}\overline{R}P$
	$P\dot{R}\dot{R}R_{sa}\overline{R}P$	$P\dot{R}\dot{R}\overline{R}R_{sa}P$	$P\dot{R}\dot{R}\overline{R}PR_{sa}$	$R_{sa}\dot{R}\dot{R}PP\overline{R}$	$\dot{R}\dot{R}R_{sa}PP\overline{R}$	$\dot{R}\dot{R}PR_{sa}P\overline{R}$	$\dot{R}\dot{R}PPR_{sa}\overline{R}$	$\dot{R}\dot{R}PP\overline{R}R_{sa}$
	$R_{sa}\dot{R}P\dot{R}P\overline{R}$	$\dot{R}P\dot{R}R_{sa}P\overline{R}$	$\dot{R}P\dot{R}PR_{sa}\overline{R}$	$\dot{R}P\dot{R}P\overline{R}R_{sa}$	$R_{sa}P\dot{R}\dot{R}P\overline{R}$	$PR_{sa}\dot{R}\dot{R}P\overline{R}$	$P\dot{R}\dot{R}R_{sa}P\overline{R}$	$P\dot{R}\dot{R}PR_{sa}\overline{R}$
	$P\dot{R}\dot{R}P\overline{R}R_{sa}$	$R_{sa}\dot{R}PP\dot{R}\overline{R}$	$\dot{R}PP\dot{R}R_{sa}\overline{R}$	$\dot{R}PP\dot{R}\overline{R}R_{sa}$	$R_{sa}P\dot{R}P\dot{R}\overline{R}$	$PR_{sa}\dot{R}P\dot{R}\overline{R}$	$P\dot{R}P\dot{R}R_{sa}\overline{R}$	$P\dot{R}P\dot{R}\overline{R}R_{sa}$
	$R_{sa}PP\dot{R}\dot{R}\overline{R}$	$PR_{sa}P\dot{R}\dot{R}\overline{R}$	$PPR_{sa}\dot{R}\dot{R}\overline{R}$	$PP\dot{R}\dot{R}R_{sa}\overline{R}$	$PP\dot{R}\dot{R}\overline{R}R_{sa}$			
3R3P	$R_{sa}\dot{R}\overline{R}PPP$	$\dot{R}R_{sa}\overline{R}PPP$	$\dot{R}\overline{R}R_{sa}PPP$	$\dot{R}\overline{R}PR_{sa}PP$	$\dot{R}\overline{R}PPR_{sa}P$	$\dot{R}\overline{R}PPPR_{sa}$	$R_{sa}\dot{R}P\overline{R}PP$	$\dot{R}R_{sa}P\overline{R}PP$
	$\dot{R}PR_{sa}\overline{R}PP$	$\dot{R}P\overline{R}R_{sa}PP$	$\dot{R}P\overline{R}PR_{sa}P$	$\dot{R}P\overline{R}PPR_{sa}$	$R_{sa}P\dot{R}\overline{R}PP$	$PR_{sa}\dot{R}\overline{R}PP$	$P\dot{R}R_{sa}\overline{R}PP$	$P\dot{R}\overline{R}R_{sa}PP$
	$P\dot{R}\overline{R}PR_{sa}P$	$P\dot{R}\overline{R}PPR_{sa}$	$R_{sa}\dot{R}PP\overline{R}P$	$\dot{R}R_{sa}PP\overline{R}P$	$\dot{R}PR_{sa}P\overline{R}P$	$\dot{R}PPR_{sa}\overline{R}P$	$\dot{R}PP\overline{R}R_{sa}P$	$\dot{R}PP\overline{R}PR_{sa}$
	$R_{sa}P\dot{R}P\overline{R}P$	$PR_{sa}\dot{R}P\overline{R}P$	$P\dot{R}R_{sa}P\overline{R}P$	$R_{sa}\dot{R}PPP\overline{R}$	$\dot{R}R_{sa}PPP\overline{R}$	$\dot{R}PR_{sa}PP\overline{R}$		

(Subscript “sa” means that it must be a sub-active joint.)

Partially-decoupled mechanism for TPMFAO (Synthesis results)



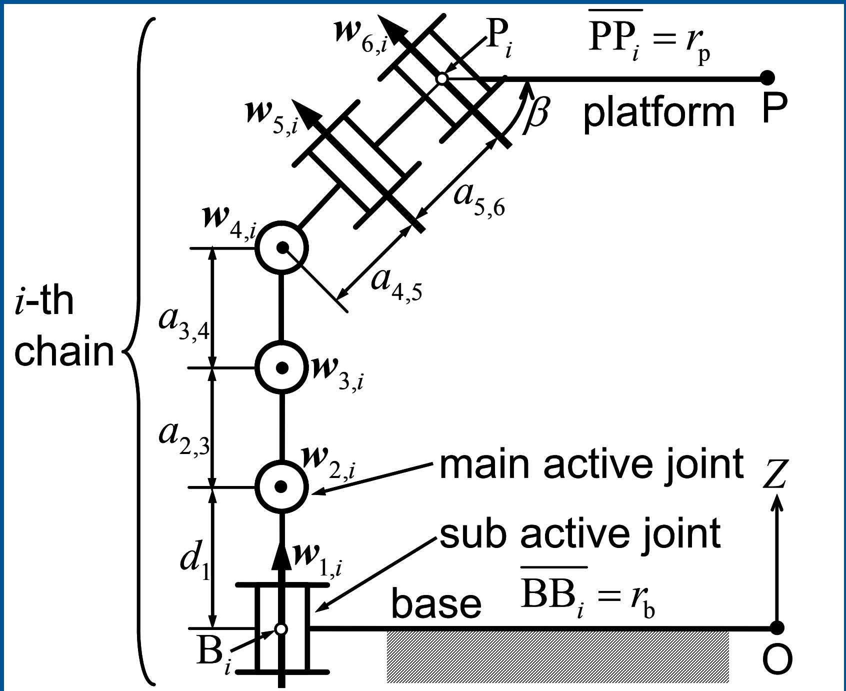
$R_{sa}\dot{R}\dot{R}\dot{R}\overline{RR}$ connecting chain
for partially-decoupled mechanism

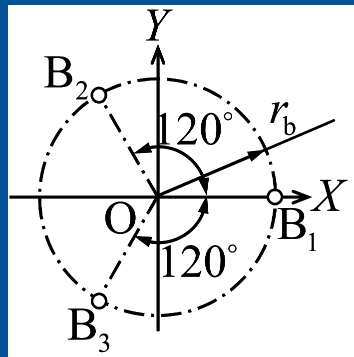
Kinematic design of prototype manipulator

Target application : assembly

Required characteristics:
- (1) large workspace
- (2) high precision
  - i. fine orientation-adjustment capability
  - ii. small coupled translational motion with rotational motion by sub-input

Mechanism configuration :





Kinematic constants of the $R_{sa}\dot{R}\dot{R}\dot{R}\overline{RR}$ partially-decoupled parallel mechanism

Kinematic design of prototype manipulator

Performance indices :

1. Singularity and utility workspace volume

constraint singularity ⟶ angle $\beta = \pi/4$

normalized volume index

$$NVI = volume\ of\ the\ utility\ workspace / (2\pi L^3/3)$$

2. Orientation-adjustment capability (OAC)

the maximum singular value of B_{PD} of J_{PD}

$$J_{\mathrm{PD}} = \begin{bmatrix} 0_3 & B_{\mathrm{PD}} \\ A_{\mathrm{PD}} & C_{\mathrm{PD}} \end{bmatrix}$$

3. Coupling index (CI)

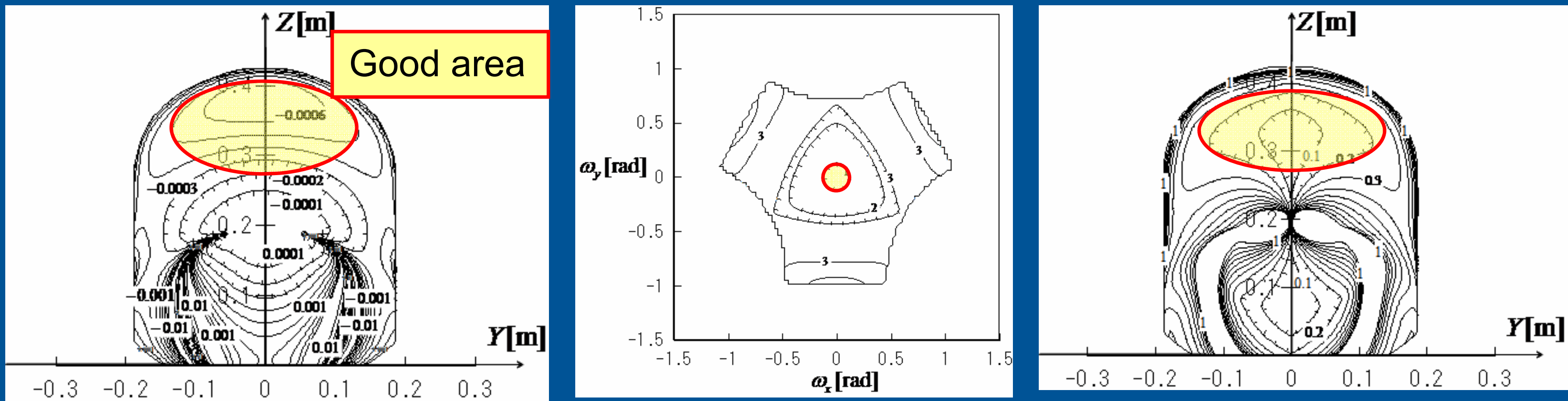
the maximum singular value of $C_{\mathrm{PD}} B_{\mathrm{PD}}^{-1}$

Kinematic design of prototype manipulator

Result :

$$r_b = 0.22\text{m},\ r_p = 0.086\text{m},\ d_1 = 0.06\text{m},\ a_{2,3} = a_{3,4} = 0.115\text{m},$$

$$a_{4,5} = 0,\ a_{5,6} = 0.19\text{m},\ \beta = \pi / 4$$

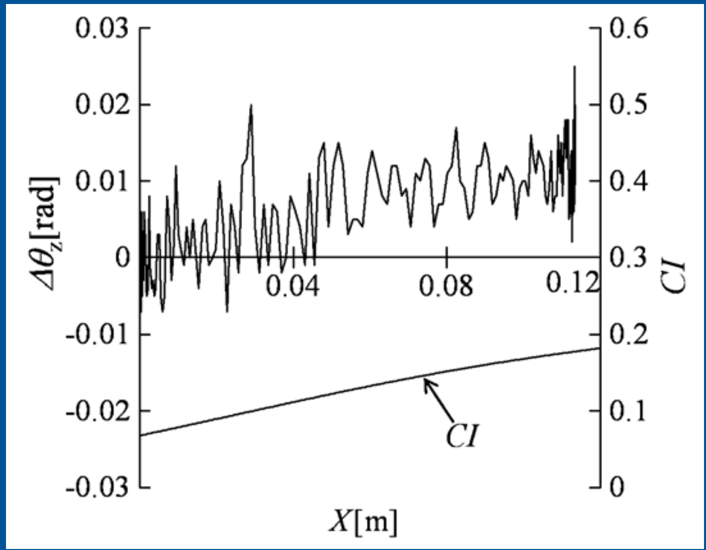


Distributions of evaluation indices in the reachable workspace

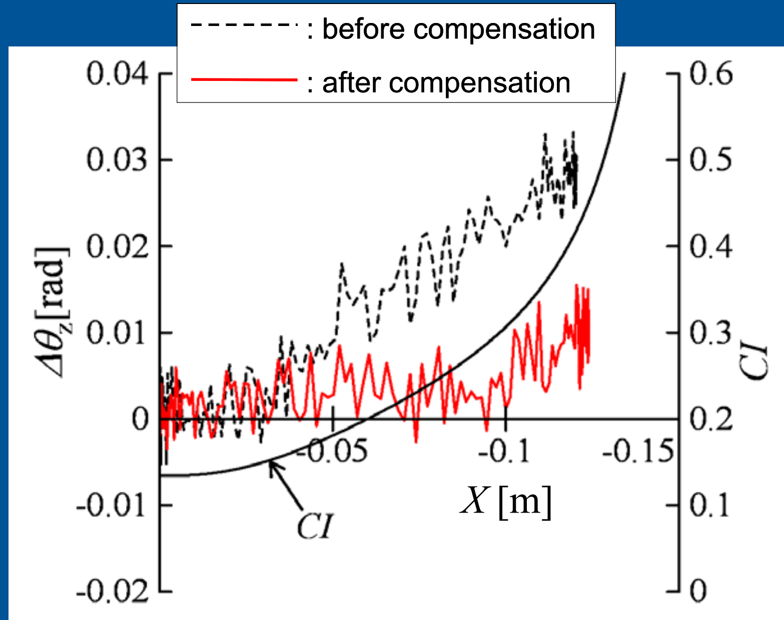
Prototype manipulator and experiments

Prototype manipulator (video of motion)

Prototype manipulator and experiments



(*X*: from 0 to 0.11m, *Y*=0, *Z*=0.35 m)



(*X*: from 0 to -0.12m, *Y*=0, *Z*=0.35 m)

Experimental results

Observations:

(1) Orientation error is large at points of large *CI*. Then, it is expected that a mechanism with small orientation error without orientation adjustment by the sub-active joints can be designed using *CI* as one of the evaluation indices in the kinematic synthesis.

(2) The orientation error of the platform was reduced by using the sub-active joints. (video of compensation motion)

Conclusions-TPMFAO

We presented a kinematic design of translational parallel manipulator with fine adjustment capability of platform orientation (TPMFAO).

1. To clarify all possible kinematic structures whose main motion is translation and sub-motion is rotation, we carried out structural synthesis of fully and partially decoupled mechanisms based on the synthesis results of 3-dof translational and rotational parallel mechanisms. As the result, we obtained 129 structures.
2. Based on the result in 1, we designed and built a prototype manipulator, and its basic characteristics were shown and discussed. It is known from the results that the coupling index is an appropriate index for the kinematic design of translational parallel manipulators for the mechanism with small orientation error without compensation.
3. Orientation adjustment of the platform by the sub-inputs of the TPMFAO was successfully achieved.

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Background

● Demand

Machine tools for 3D-shaped objects

Aspherical lens, objects with free-form surfaces

● Required characteristics

- Ability to change the tool orientation around two axes within a large range of motion
- Ability to precisely keep the position of the center of rotation of the tool and orientation of the tool
- Decoupled motion(translation and rotation)

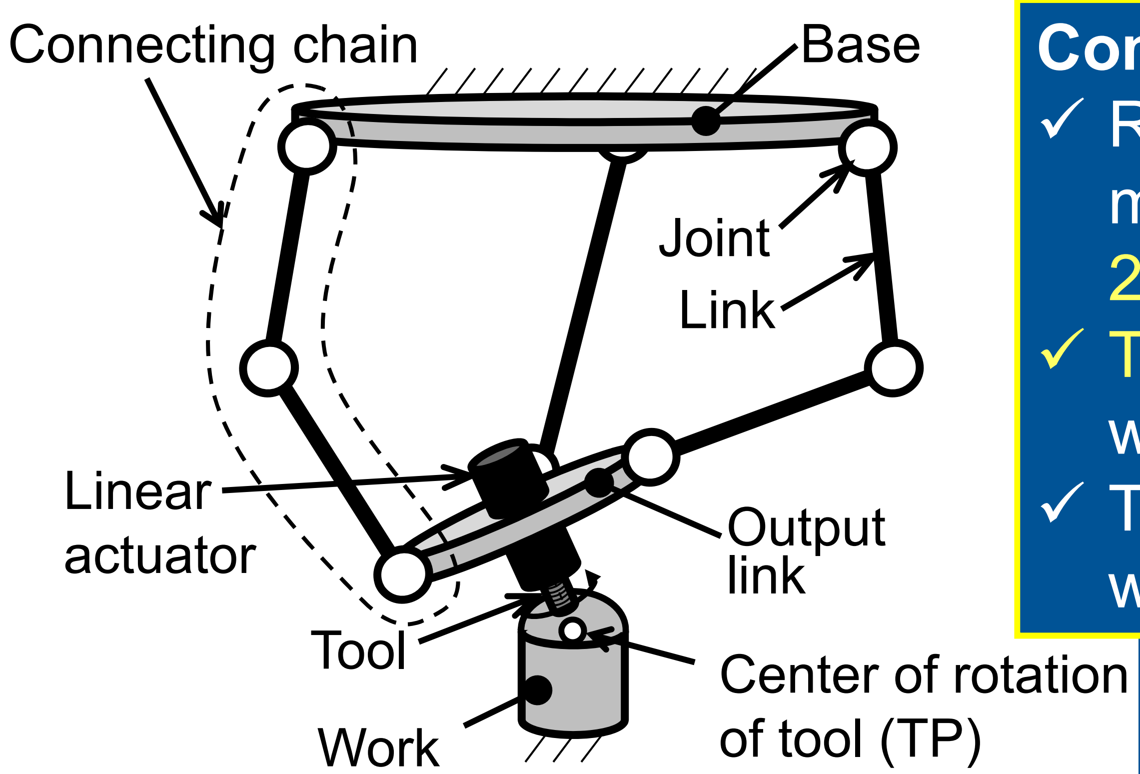
Under the conditions of

✓ Large machining load

✓ No physical supporting elements at TP

TP (Target point): center of rotation of the tool

Configuration of proposed machine tool

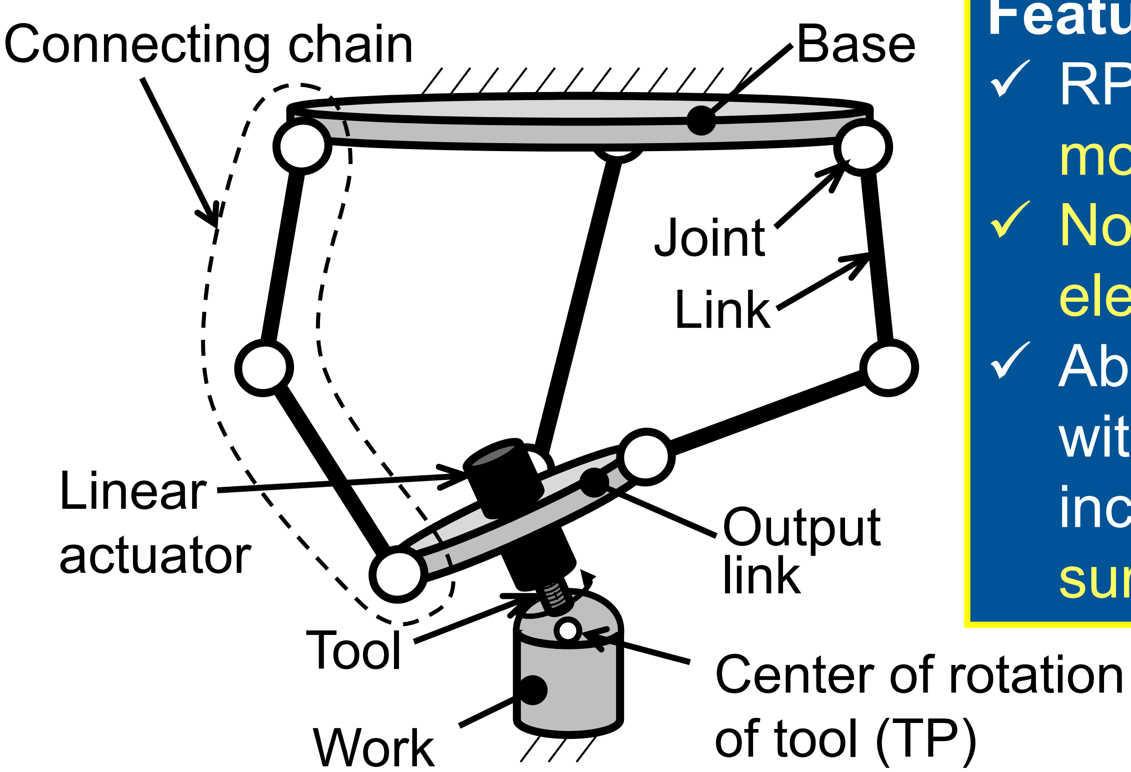


Composition

- ✓ Rotational parallel mechanism (RPM) with 2dof
- ✓ Translational mechanism with 1dof
- ✓ Translational mechanism with 3dof (not shown)

Machine tool using rotational parallel mechanism

Configuration of proposed machine tool



Features

- ✓ RPM performs 2-dof rotational motion around TP
- ✓ No physical supporting elements at TP
- ✓ Ability to manufacture objects with free-form surfaces, including concave and convex surfaces

Machine tool using rotational parallel mechanism

Purpose of research

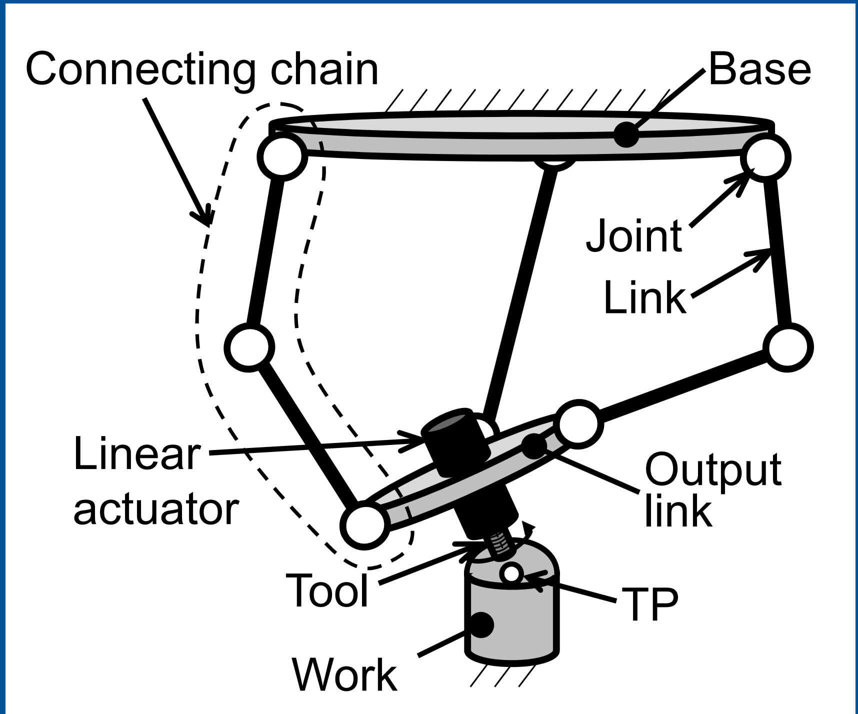
Problems to be solved (focused on RPM)

- ✓ To precisely keep the position of TP without physical supporting elements at TP
- ✓ To achieve a large orientation around 2 axes

Approach

- ✓ Structural and dimensional synthesis of RPM

A mechanism that theoretically achieves rotational output motion around two axes can be synthesized by considering the constraints by the connecting chains imposed on the output link.
However,



Configuration of proposed machine tool

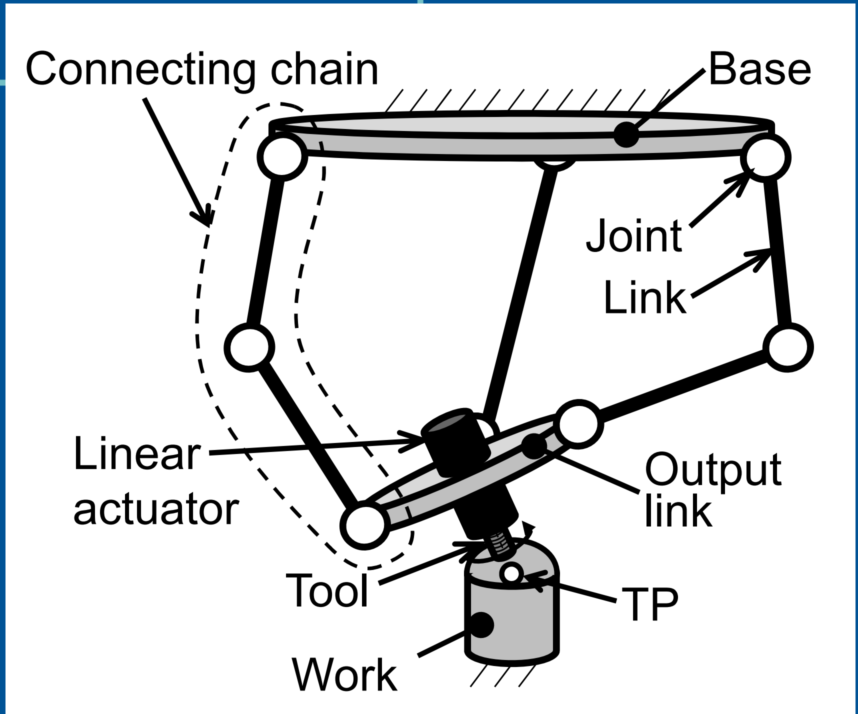
Purpose of research

Consideration to the position error of TP (uncompensatable error by RPM)

Position error of TP, that is caused by manufacturing and assembly errors and elastic deformation of parts, cannot be compensated for by RPM itself.

Purpose of research

Structure and dimensions of mechanism, that can perform 2dof translational motion in the output link's plane as well as 2dof rotational motion, is proposed.



Configuration of proposed machine tool

Related works

- Rotational parallel mechanism
- ✓ Structural synthesis (Kong, 2004) (Karouia, 2005)
- ✓ Dimensional synthesis taking into consideration workspace, singularity, and motion transmissibility (Takeda, 1996), (Huda, 2007)
- Uncomsatable error (parasitic motion) of lower-dof PM
- ✓ Kinematic synthesis of 3-URU pure RPM based on sensitivity analysis(Huda, 2008)
- ✓ Kinematic calibration of a translational PM (Huang, 2003)
- ✓ Kinematic design of translational PM with orientation error compensation function (Tanabe, 2010)

However, we have not found any rotational mechanisms that achieve precise positioning of the target point within a large workspace or any method for designing such a mechanism.

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2. Structural Synthesis

Basic condition

(1) Connecting chains are composed of prismatic and revolute joints.
(2) Overconstrained, redundant, and redundant actuation mechanisms are not considered.
(3) There are three connecting chains. This condition was determined by considering the stiffness characteristics of the mechanism in all directions, avoidance of collisions between links, and cost reduction.
(4) The mechanism has four DOF. Two of them are used for orientation control of the output link within a large workspace, and the other two are used for fine compensation for position error of the target point.
(5) Two of the three connecting chains have the same structure and kinematic constants.

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Function of connecting chains

- **Required output motion (total 4 dof):**
  - ✓ rotational motion with 2 dof as the main output motion
  - ✓ translational motion with 2 dof as the compensation motion
- **Classification and function of connecting chains**
- **Constraint chain (one)**

(1)composed of passive joints
(2)constraint force perpendicular to the output link's plane and passing through TP
(3) constraint moment around 1 axis

- **Actuation chains (two) (for each)**

(1)two active joints
(2)one active joint corresponds to rotational output motion
(3)the other active joint corresponds to translational output motion

2. Structural Synthesis

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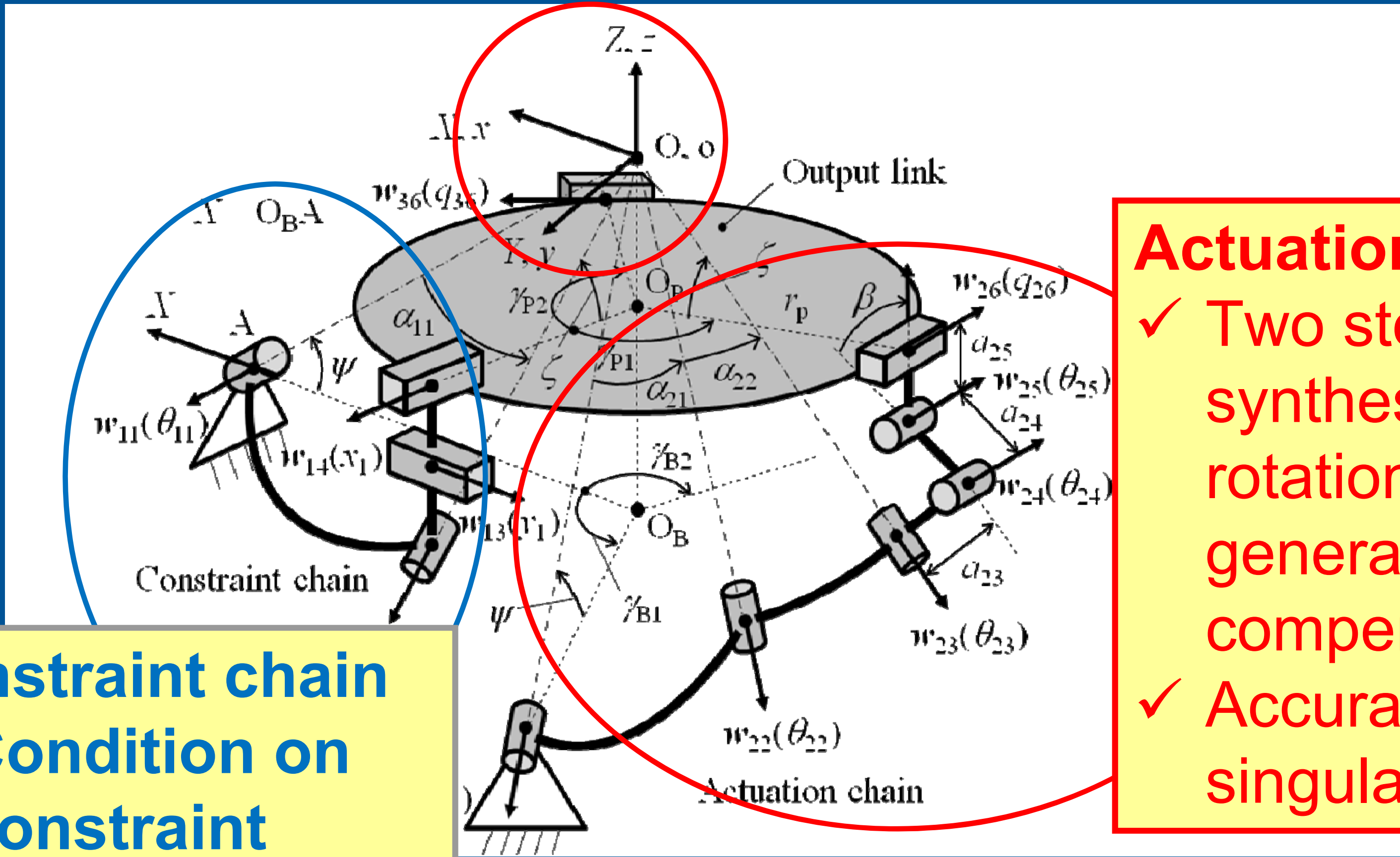
Result



Actuation chains
- ✓ Two step synthesis for rotational motion generation and compensation
- ✓ Accuracy and singularity

Constraint chain
- ✓ **Condition on constraint**

Kinematic structure of synthesized mechanism

(In the figure, the other actuation chain is not shown.)

3. Dimensional Synthesis

Evaluation indices

(1) For output velocity characteristics

(2) For torque transmissibility

(3) For decoupling characteristics in compensation motion

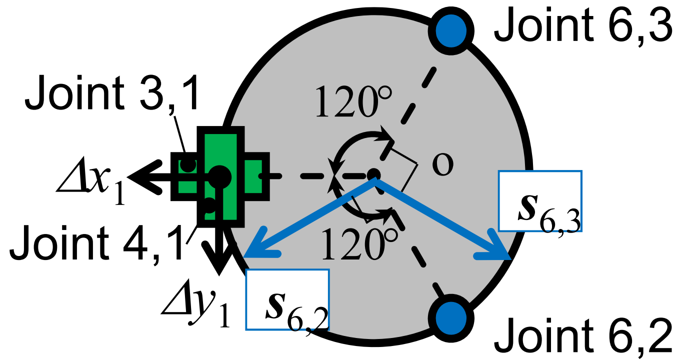
Synthesis procedure composed of two steps

(1) Determination of kinematic constants regarding rotational output motion based on indices (1) and (2)

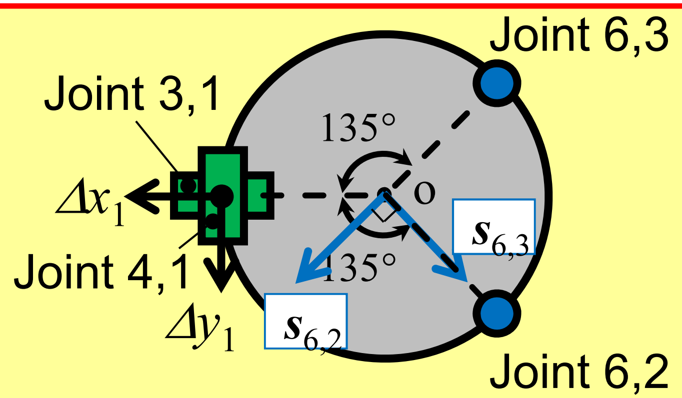
(2) Determination of kinematic constants regarding compensation motion based on indices (3)

3. Dimensional Synthesis

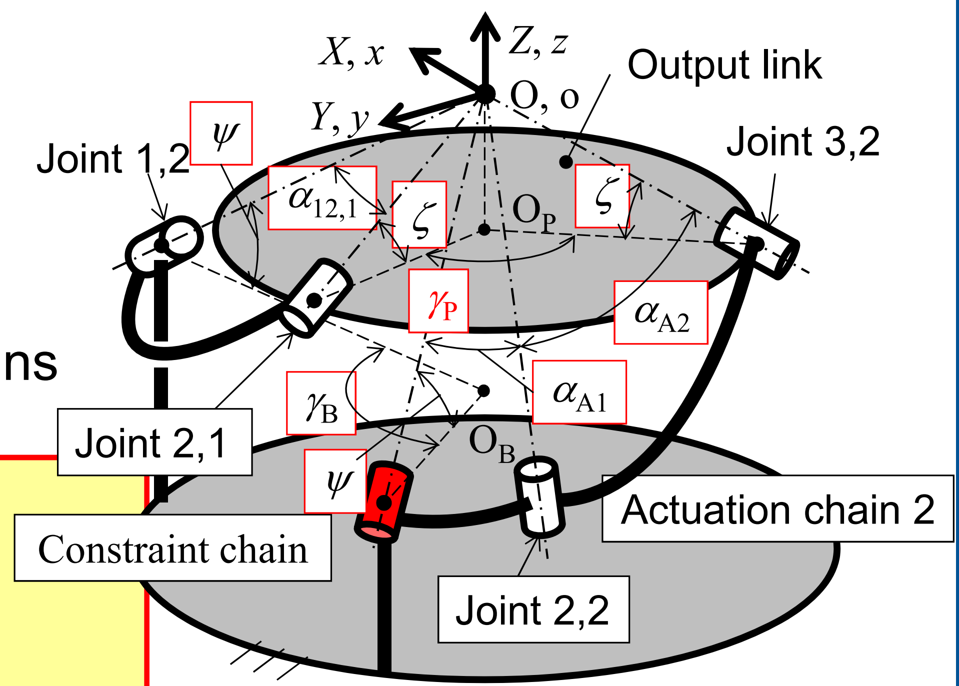
Determination of kinematic constants regarding rotational output motion



Symmetrical arrangement of three chains



Orthogonal arrangement of actuation chains



Related design parameters

Evaluation indices: I_A and I_S

3. Dimensional Synthesis

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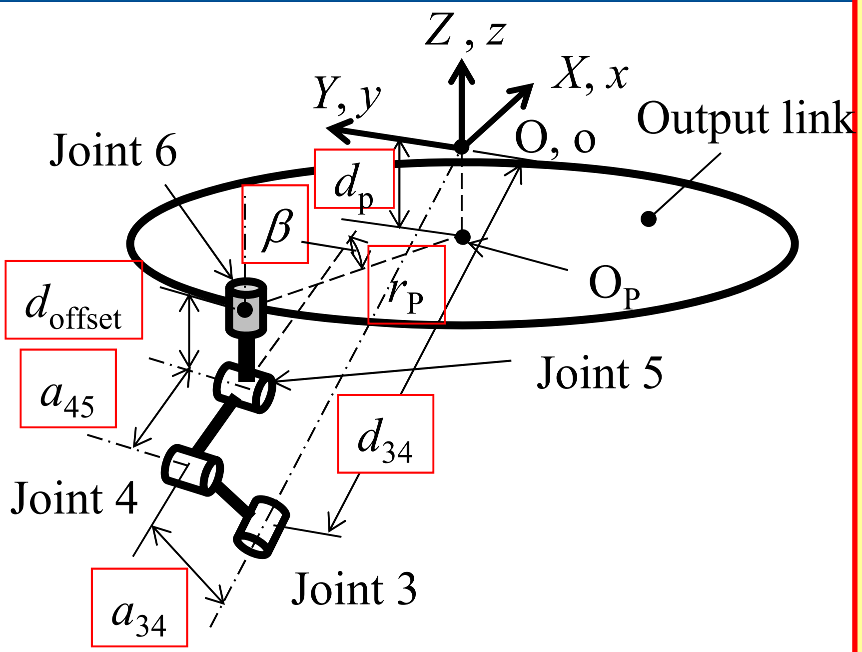
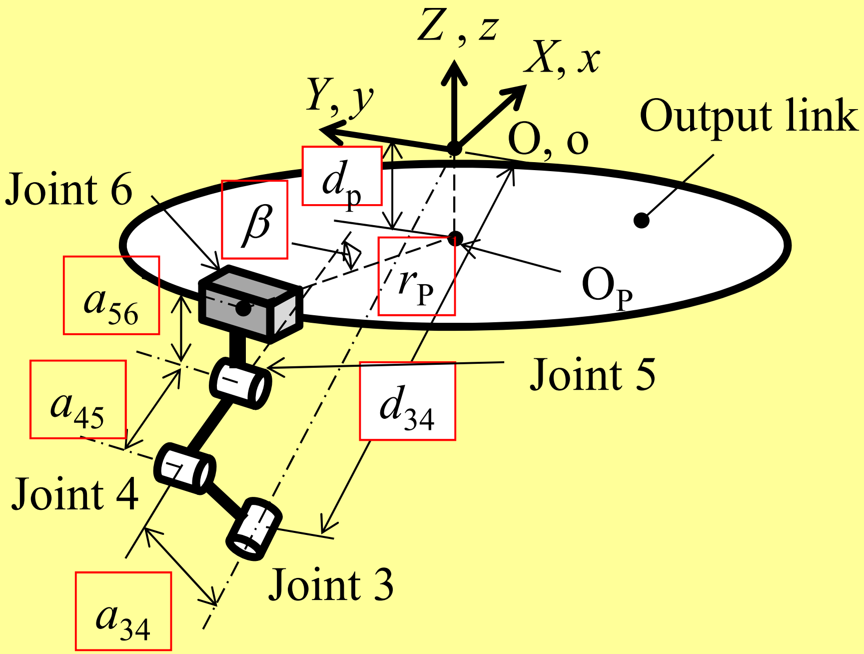
Determination of kinematic constants regarding compensation motion



Type A (revolute joint)



Type B (prismatic joint)

Related design parameters

Evaluation index: *CI*

3. Dimensional Synthesis

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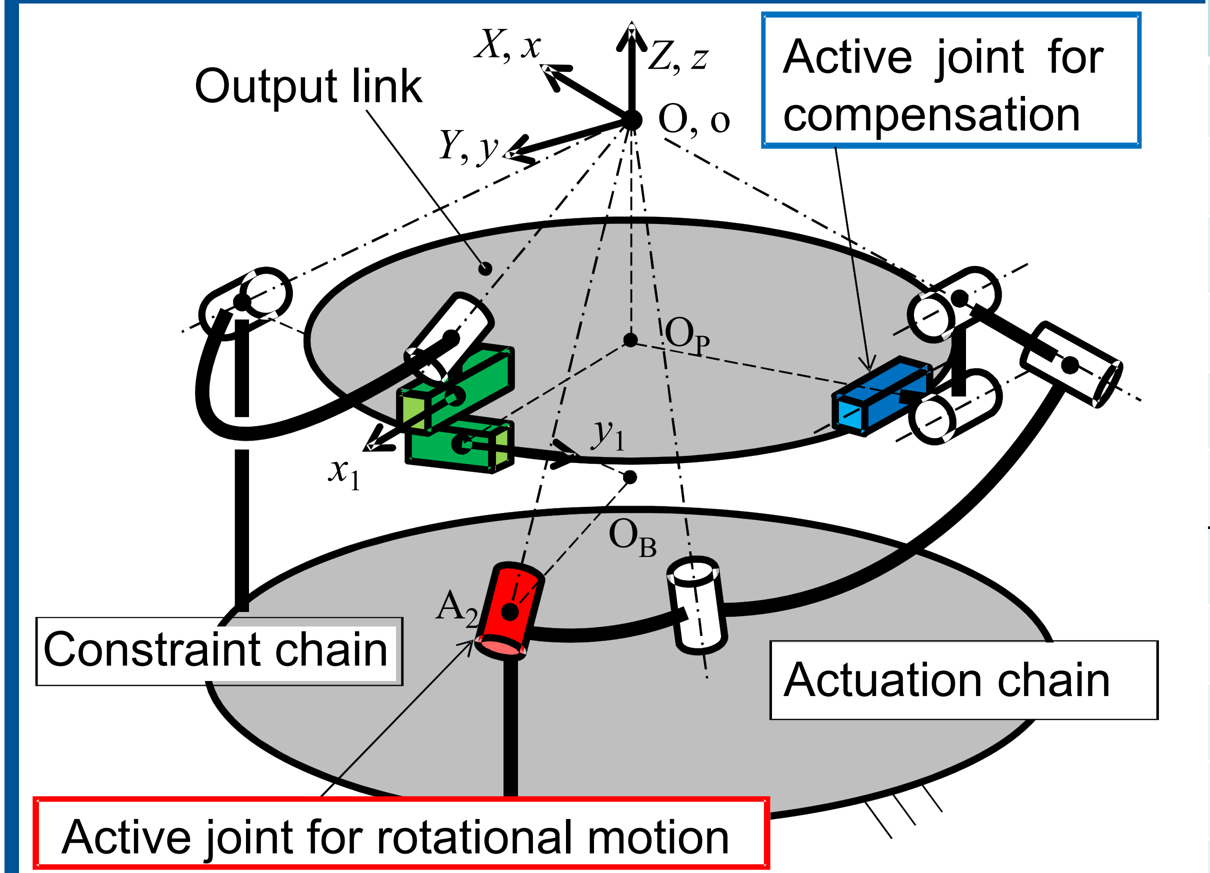
Result **(In the figure, the other actuation chain is not shown.)**

Specification: $0 \le \theta_y \le 60^\circ,\ 0 \le \theta_z \le 360^\circ$



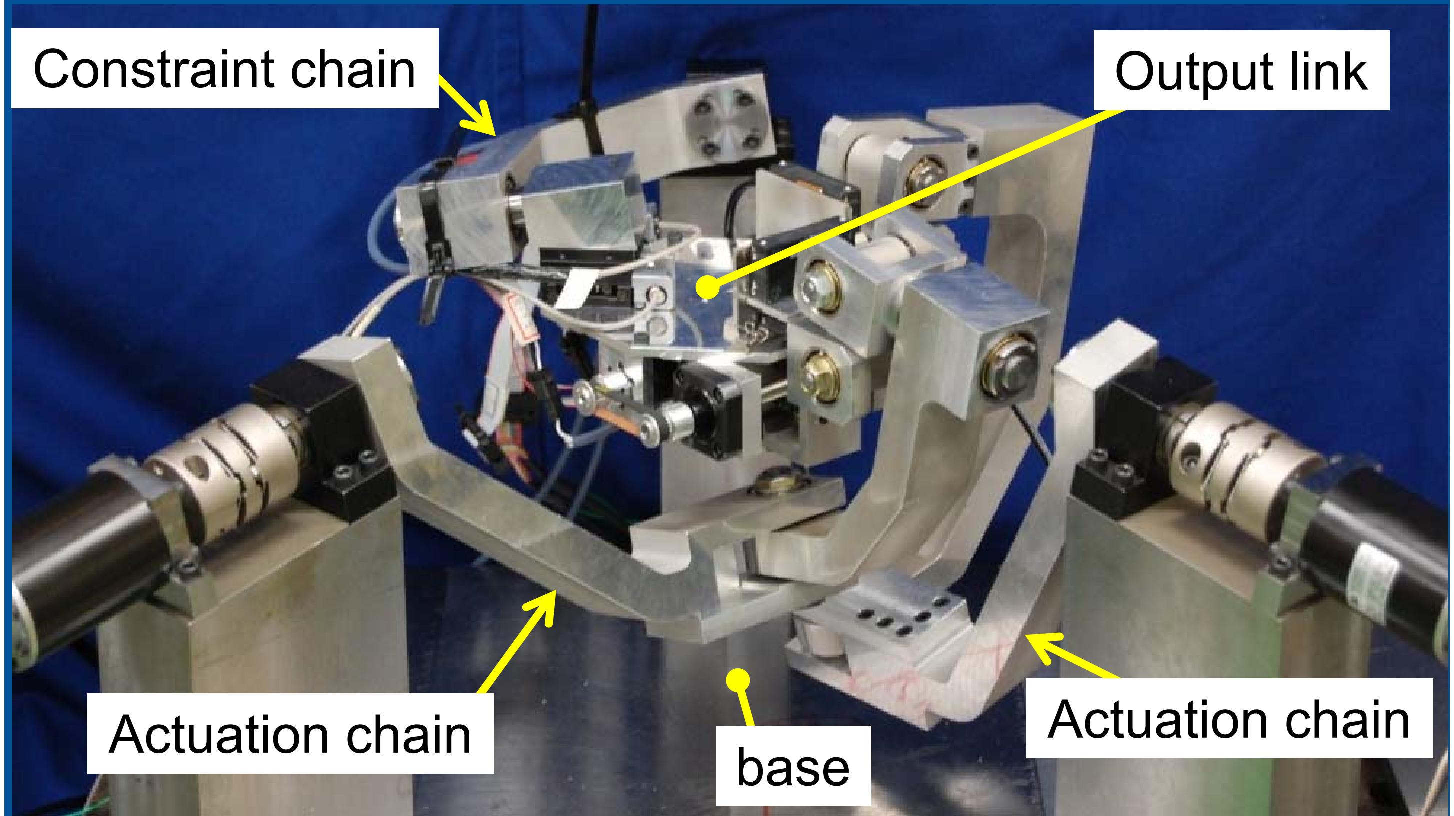
Synthesized mechanism

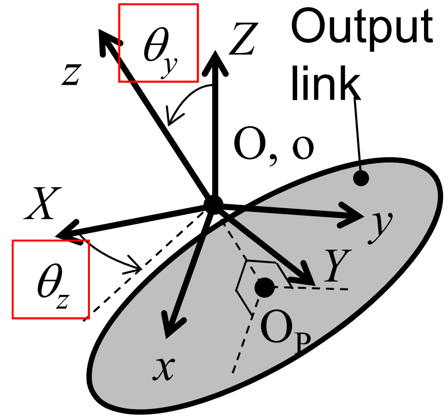
Kinematic constants

Parameter	value
$\alpha_{12,1}$	82°
α_{A1}	78°
α_{A2}	65°
ψ	10°
ζ	10°
γ_P, γ_B	135°
a_{34}	0 mm
a_{45}	40 mm
a_{56}	0 mm
d_{34}	91.39 mm
β	-90°
d_P	55.87 mm
r_P	90 mm

4. Experiments

Design and fabrication of prototype





Orientation of output link

Workspace:

$$0° \le \theta_y \le 60°$$

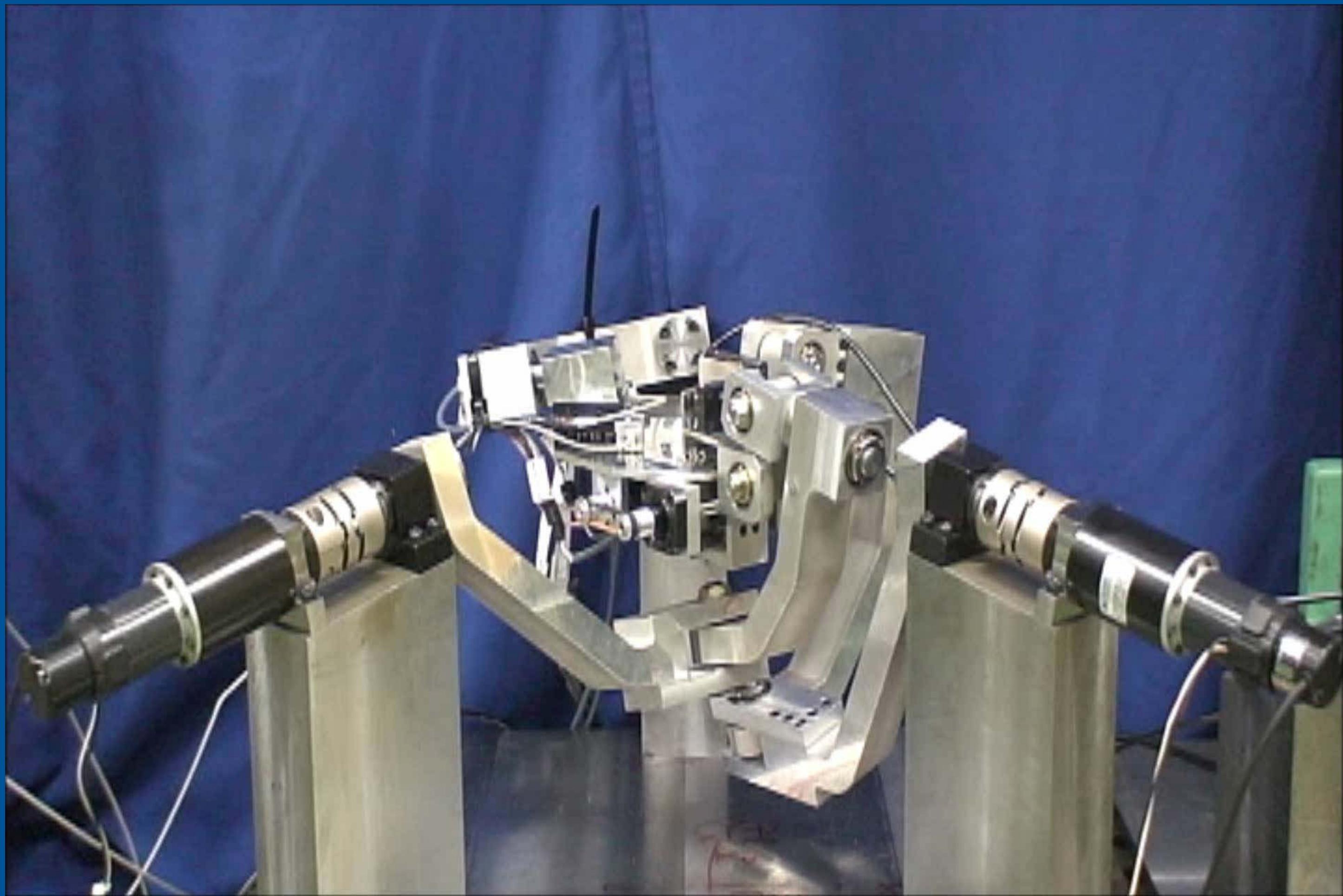
$$0° \le \theta_z \le 360°$$

Overview of prototype

- ✓ Collision between links
- ✓ Stiffness of links and mechanism

4. Experiments

Experiment (workspace: rotational motion)



$(\theta_y = 60^\circ)$

4. Experiments

Experiment (workspace: compensation motion)

Composition of actuator for compensation and motion

Lead of ball screw 1mm
Resolution of linear scale 0.2μm

4. Experiments

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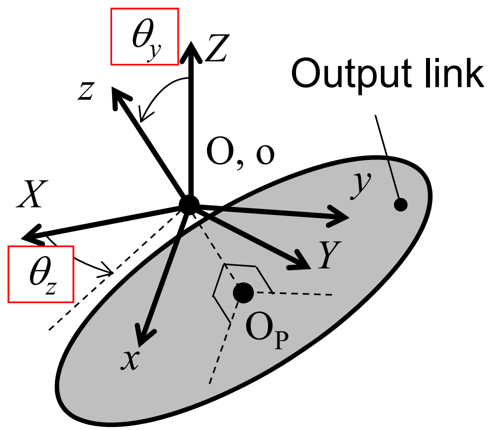
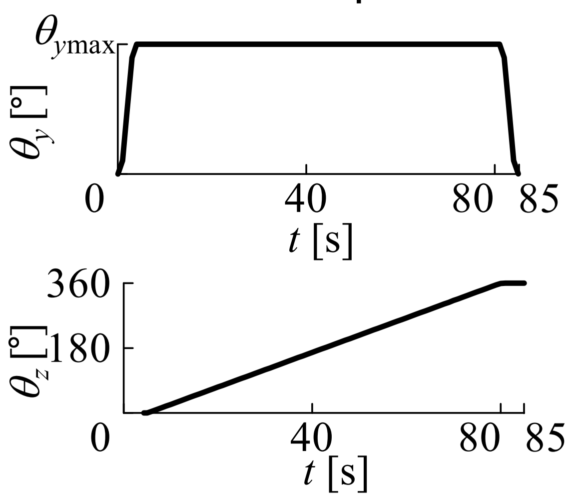
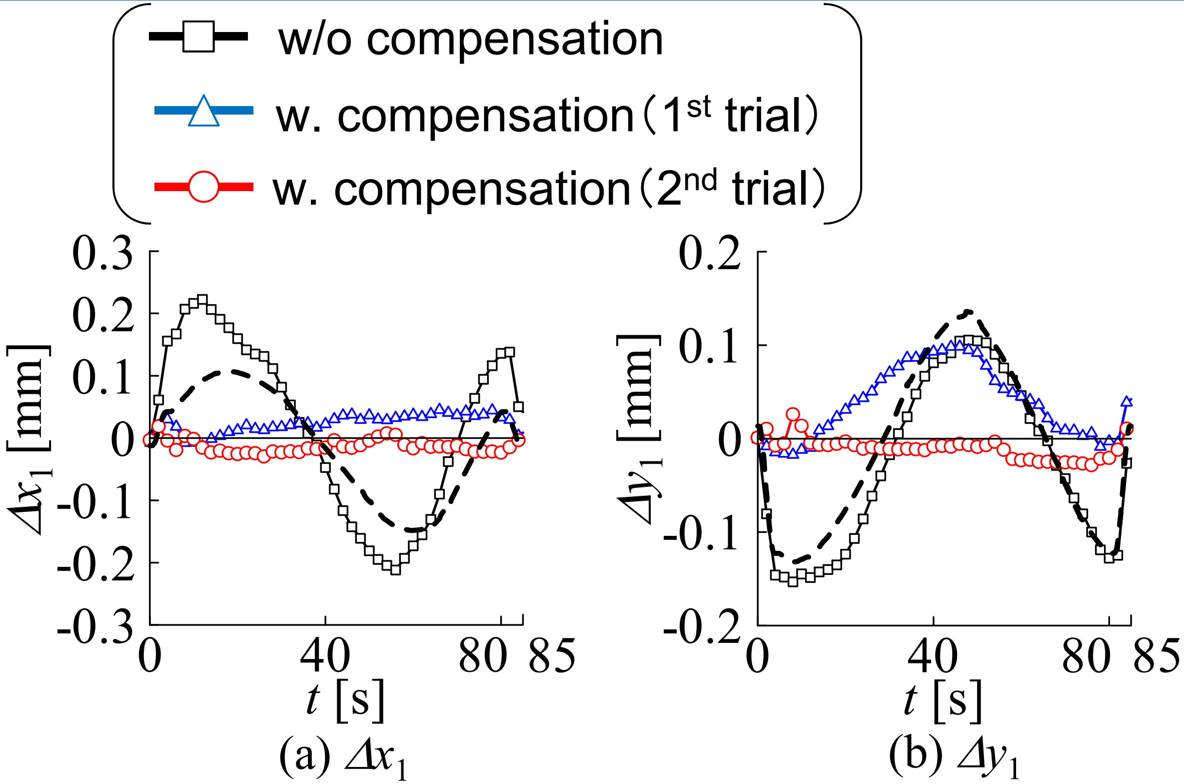
Experiment (compensation of position error of TP)



Orientation of output link



Reference trajectory



Measured position error of TP ($\theta_{y\max} = 15°$)

4. Experiments

Tokyo Institute of Technology
Mechanical Systems Design Lab.

Experiment (compensation of position error of TP)

Maximum values of position error

θ_{ymax}[°]	w/o compensation		1st compensation		2nd compensation	
	Δx_1[mm]	Δy_1[mm]	Δx_1[mm]	Δy_1[mm]	Δx_1[mm]	Δy_1[mm]
15	0.228	0.166	0.054	0.104	0.039	0.045
30	0.642	0.323	0.153	0.111	0.055	0.076
45	1.196	0.489	0.364	0.117	0.159	0.106
60	1.765	0.653	0.486	0.132	0.144	0.106

RMS values of position error

θ_{ymax}[°]	w/o compensation		1st compensation		2nd compensation	
	Δx_1[mm]	Δy_1[mm]	Δx_1[mm]	Δy_1[mm]	Δx_1[mm]	Δy_1[mm]
15	0.137	0.094	0.027	0.054	0.017	0.016
30	0.333	0.200	0.075	0.069	0.017	0.017
45	0.560	0.295	0.151	0.052	0.047	0.044
60	0.789	0.380	0.202	0.043	0.066	0.039

5. Conclusions-RPMFAP

To develop a precise rotational parallel mechanism with two DOF, structural and dimensional syntheses of a mechanism with two actuators for generating rotational output motion and two actuators for compensating for position error of the target point were carried out. Our conclusions are summarized as follows.

(1) A kinematic structure of a mechanism with three connecting chains was proposed.

(2) Dimensional synthesis of the mechanism proposed in (1) was carried out, taking into consideration singular configurations and rotational output motion coupled with translational motion for compensation.

(3) A large orientation workspace, with an output link inclination angle of up to 60° and compensation for position error of the target point was successfully achieved by our prototype mechanism.

Application to machine tool

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Table of contents-RPMVTP

Target applications

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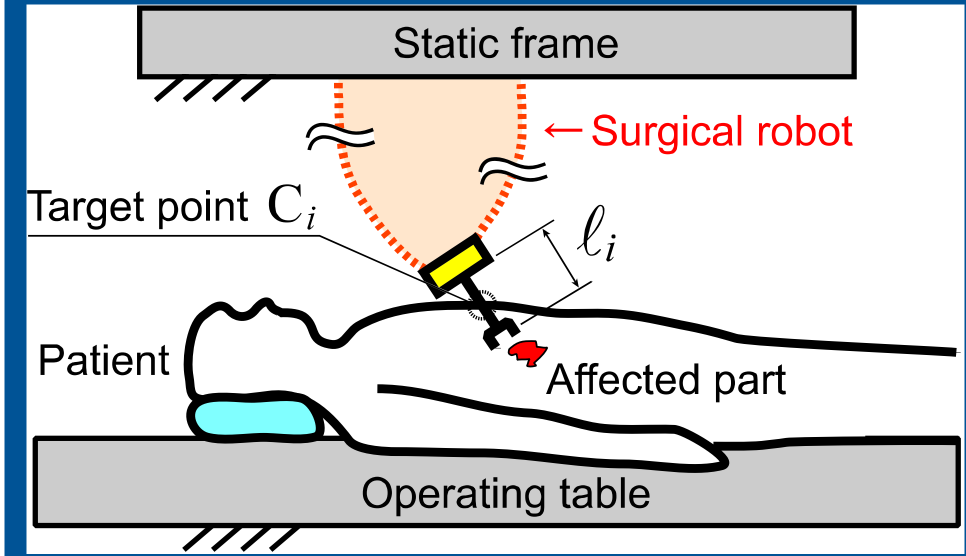
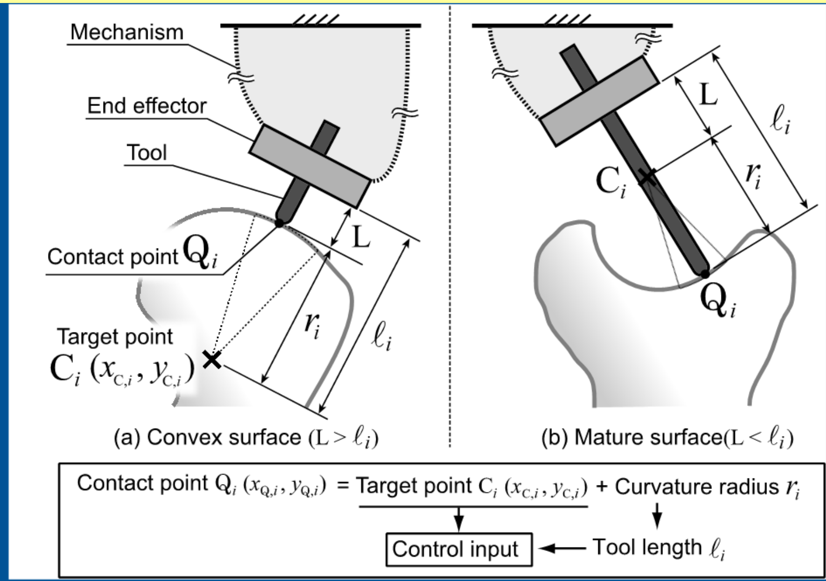


Minimum invasive surgery

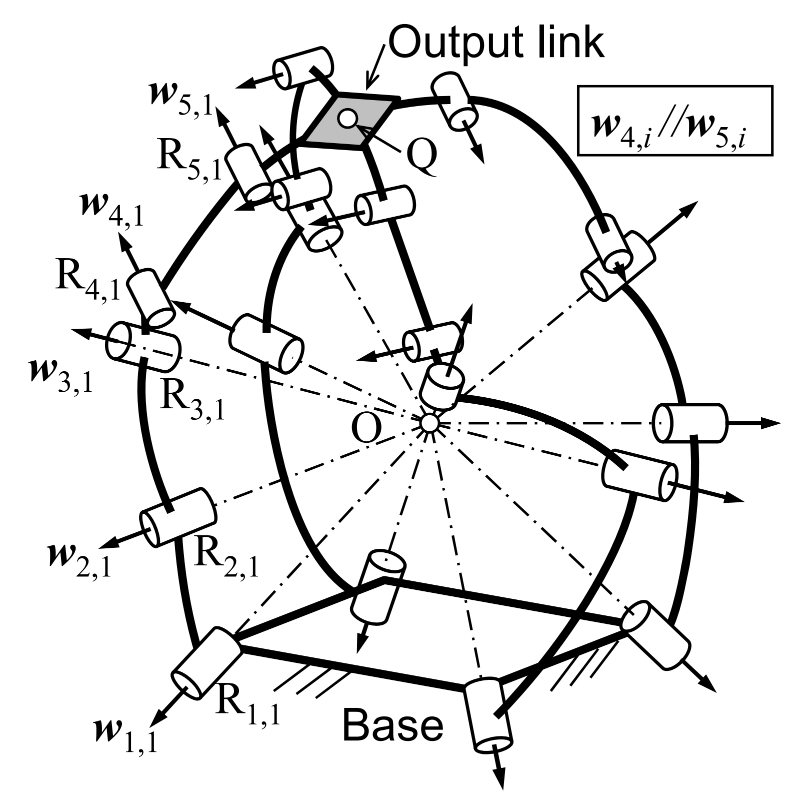


Manufacturing of prostheses

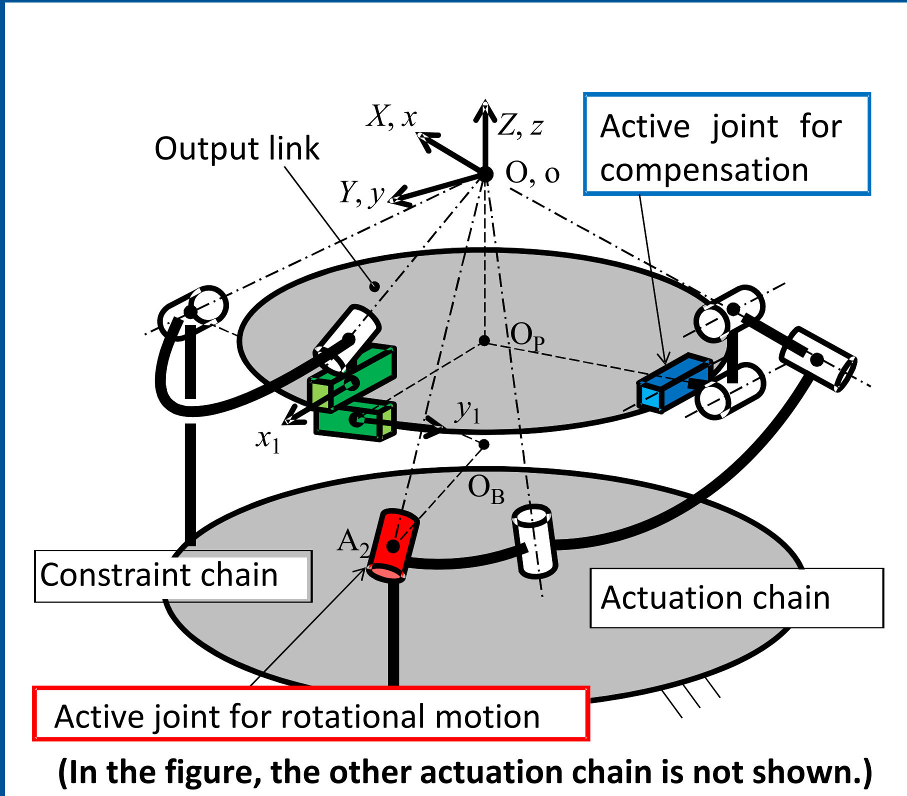
There are a lot of operations done by robots that require precise rotational output motion around two axes while the position of the rotation center (hereafter, we call "target point") being changed in a three dimensional space. Examples are shown above. In both cases, the actuators should be remotely located from the operation area in order that they would be protected from the working environment.
We are under development of the parallel mechanism with asymmetrical structure for such applications (2R3T output motion with 5 dof).

Previous works

Rotational/Spherical mechanisms with variable TP



Four-dof 3R1T parallel mechanism
(Zlatanov and Gosselin, 2001)



Four-dof 2R2T parallel mechanism
(Okamura, Hanagasaki, Takeda, 2011)

Examples of 4 DOF mechanism

Previous works

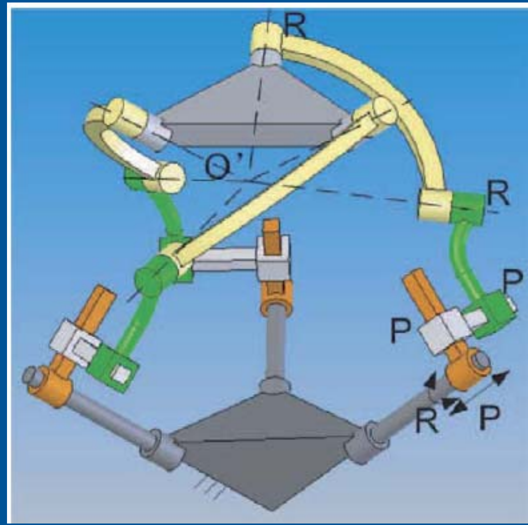
position-orientation decoupled mechanism with 6 dof

Symmetrical structures:

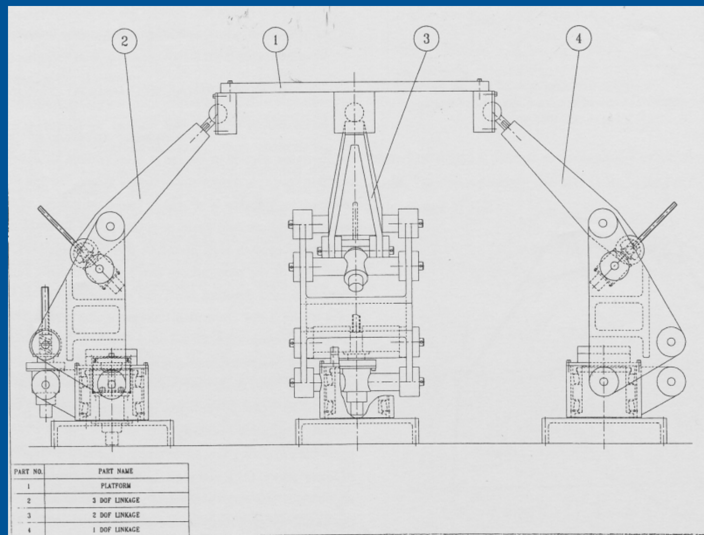
✓ C. Innocenti, V. Parenti-Castelli, 1991.
✓ K. Wohlhart , 1994.
✓ S. P. Patarinski, M. Uchiyama, 1995.
✓ K. Mianovski, 1998.
✓ Y. Takeda, et al, 2005.
✓ Y. Jin, I-M. Chen, G. Yang, 2006.

Asymmetrical structures:

✓ D. Zlatanov, et al, 1992.
✓ Z.J.Geng, L.Haynes, 1994.



Jin, Chen and Yang, 2006.

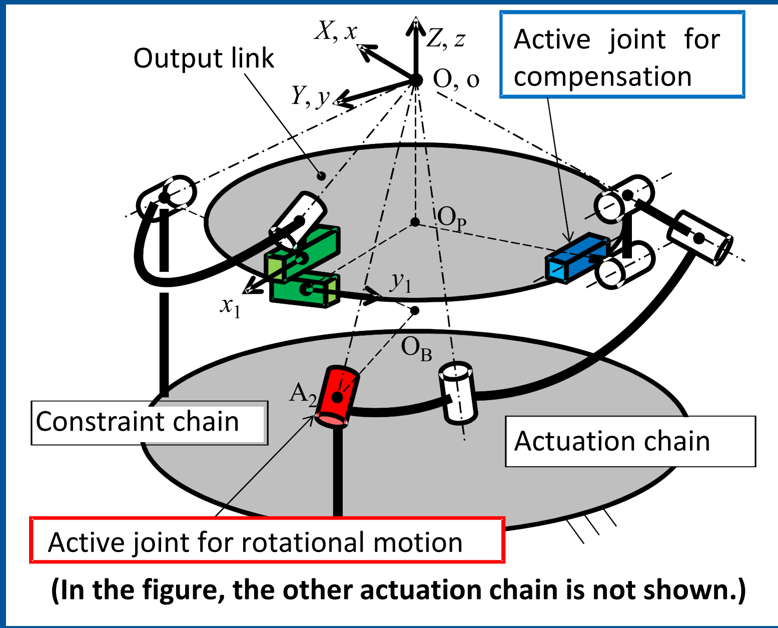


Zlatanov, et al, 1992

Previous works

Asymmetrical decoupled mechanism with limited dof

- ✓ S. Refaat, J.M.Herve, 2006. (1R2T and 2R1T mechanisms with 3 dof have been proposed based on Lie-group theory)
- ✓ J. Okamura, S. Hanagasaki, Y. Takeda, 2011 (2R2T mechanism with 4 dof have been developed)
- ✓ C.C.Lee, J.M.Herve, 2012. (1R3T and 2R3T mechanisms with 4 or 5 dof have been introduced, where rotational motions are infinitesimal.)



Previous mechanism by the authors' group. Actuators for translational motion are located on the output link.

Kinematic structures of mechanism in which all actuators are located on or close to the base are clarified in this research.

Purpose of the research

- To figure out kinematic structures of asymmetrical five-DOF fully decoupled parallel mechanism, in which rotational motion of the output link around two axes is controlled by two inputs while translational motion of the target point, the center of rotation of the output link, is controlled by the other three inputs.
- To derive equations for displacement and velocity analyses and to clarify basic characteristics such as input-output relationship and singularity for a concrete structure.

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Basic structure of RPMVTP

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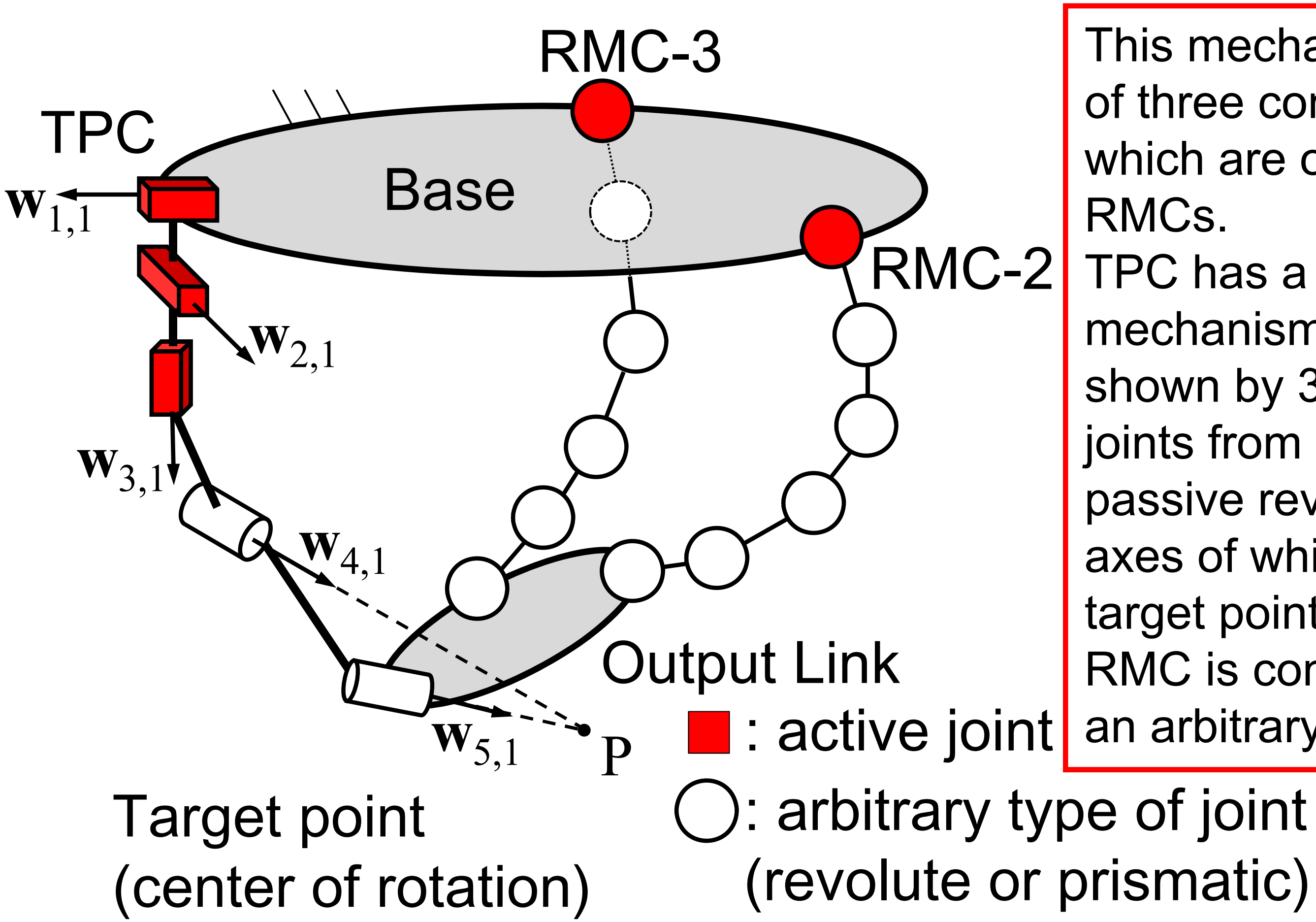
Mechanism configuration



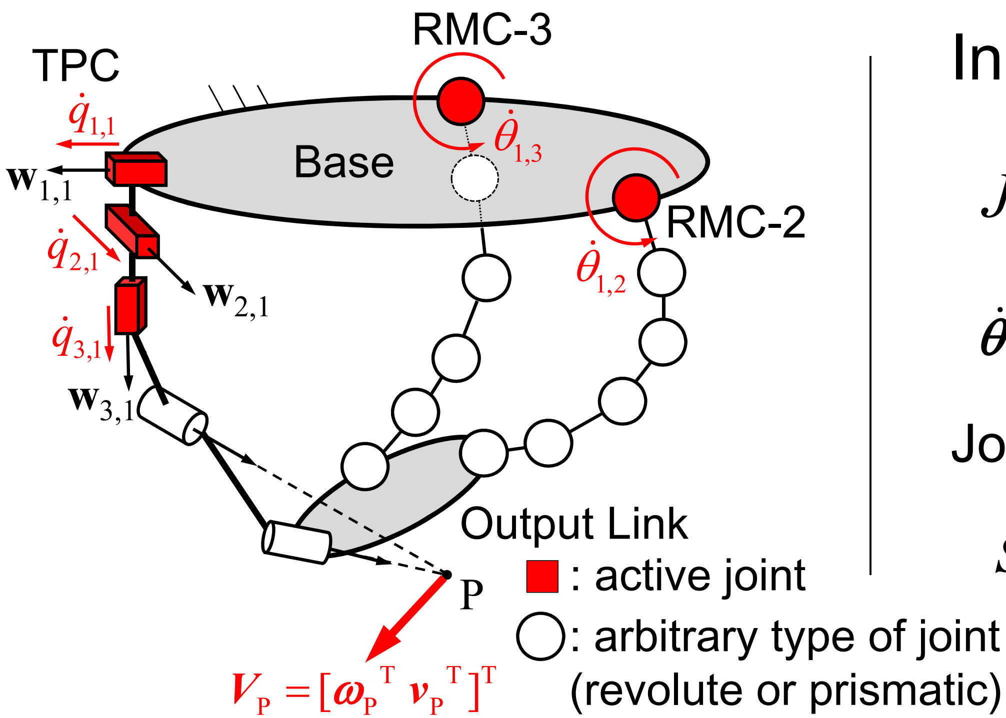
This mechanism is composed of three connecting chains, which are one TPC and two RMCs.
TPC has a translational mechanism with 3 DOF, shown by 3 active prismatic joints from the base and two passive revolute joints, the axes of which meet at the target point.
RMC is considered to have an arbitrary structure.

RMC (Rotational motion generating chain): 6 dof
TPC (Target point controlling chain): 5 dof (3T2R)

Basic structure of RPMVTP

Tokyo Institute of Technology
Mechanical Systems Design Lab.

Velocity relationship (Jacobian matrix)



Input-output relationship:

$$J_{\mathrm{T}} \begin{bmatrix} \boldsymbol{\omega}_{\mathrm{P}} \\ \boldsymbol{v}_{\mathrm{P}} \end{bmatrix} = \begin{bmatrix} J_{\mathrm{A}} & J_{\mathrm{B}} \\ 0 & J_{\mathrm{C}} \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega}_{\mathrm{P}} \\ \boldsymbol{v}_{\mathrm{P}} \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{\theta}} \\ \dot{\boldsymbol{q}} \end{bmatrix}$$

$$\dot{\boldsymbol{\theta}} = [\dot{\theta}_{1,2} \quad \dot{\theta}_{1,3} \quad 0]^{\mathrm{T}} \qquad \dot{\boldsymbol{q}} = [\dot{q}_{1,1} \quad \dot{q}_{2,1} \quad \dot{q}_{3,1}]^{\mathrm{T}}$$

Joint screw:

$$\boldsymbol{S}_{1,i} = \begin{bmatrix} \hat{\boldsymbol{\omega}}_{1,i} \\ \hat{\boldsymbol{v}}_{1,i} \end{bmatrix}$$

Constraint wrench:

$$\boldsymbol{S}_{\mathrm{RA},i} = \begin{bmatrix} \hat{\boldsymbol{f}}_i \\ \hat{\boldsymbol{m}}_i \end{bmatrix}$$

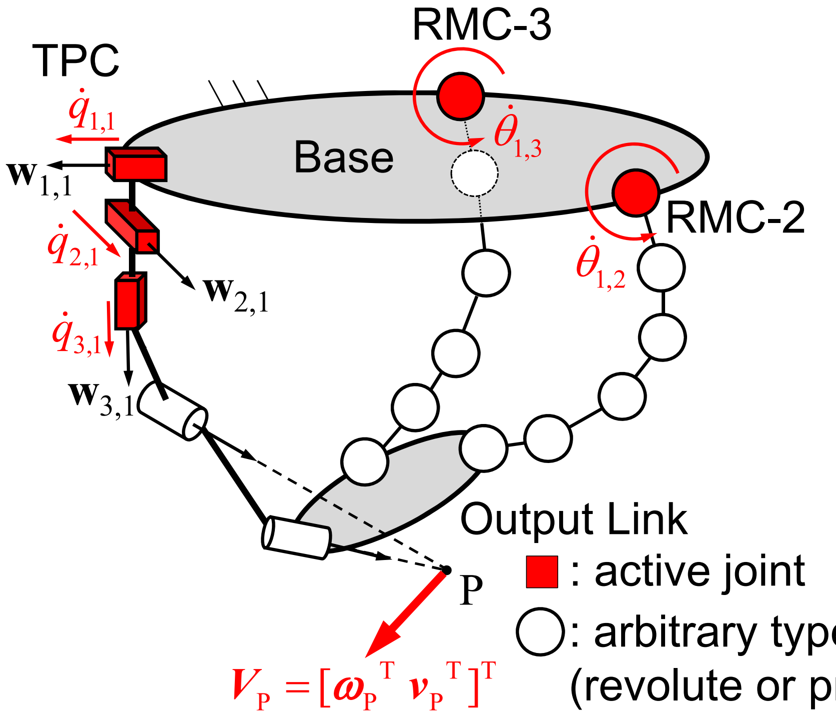
(of active joints of RMCs)

Sub-matrices of Jacobian matrix J_{T}:

$$J_{\mathrm{A}} = \begin{bmatrix} \dfrac{\hat{\boldsymbol{m}}_2{}^{\mathrm{T}}}{\hat{\boldsymbol{m}}_2{}^{\mathrm{T}} \hat{\boldsymbol{\omega}}_{1,2} + \hat{\boldsymbol{f}}_2{}^{\mathrm{T}} \hat{\boldsymbol{v}}_{1,2}} \\ \dfrac{\hat{\boldsymbol{m}}_3{}^{\mathrm{T}}}{\hat{\boldsymbol{m}}_3{}^{\mathrm{T}} \hat{\boldsymbol{\omega}}_{1,3} + \mathrm{f}_3{}^{\mathrm{T}} \hat{\boldsymbol{v}}_{1,3}} \\ (\boldsymbol{w}_{4,1} \times \boldsymbol{w}_{5,1})^{\mathrm{T}} \end{bmatrix}, \quad J_{\mathrm{B}} = \begin{bmatrix} \dfrac{\hat{\boldsymbol{f}}_2{}^{\mathrm{T}}}{\hat{\boldsymbol{m}}_2{}^{\mathrm{T}} \hat{\boldsymbol{\omega}}_{1,2} + \hat{\boldsymbol{f}}_2{}^{\mathrm{T}} \hat{\boldsymbol{v}}_{1,2}} \\ \dfrac{\hat{\boldsymbol{f}}_3{}^{\mathrm{T}}}{\hat{\boldsymbol{m}}_3{}^{\mathrm{T}} \hat{\boldsymbol{\omega}}_{1,3} + \hat{\boldsymbol{f}}_3{}^{\mathrm{T}} \hat{\boldsymbol{v}}_{1,3}} \\ \boldsymbol{0} \end{bmatrix}, \quad J_{\mathrm{C}} = \begin{bmatrix} \boldsymbol{w}_{1,1}{}^{\mathrm{T}} \\ \boldsymbol{w}_{2,1}{}^{\mathrm{T}} \\ \boldsymbol{w}_{3,1}{}^{\mathrm{T}} \end{bmatrix}$$

Basic structure of RPMVTP

Velocity relationship (forward velocity analysis)



Input-output relationship:

$$J_T \begin{bmatrix} \boldsymbol{\omega}_P \\ \boldsymbol{v}_P \end{bmatrix} = \begin{bmatrix} J_A & J_B \\ 0 & J_C \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega}_P \\ \boldsymbol{v}_P \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{\theta}} \\ \dot{\boldsymbol{q}} \end{bmatrix}$$

$$\dot{\boldsymbol{\theta}} = [\dot{\theta}_{1,2} \quad \dot{\theta}_{1,3} \quad 0]^T \qquad \dot{\boldsymbol{q}} = [\dot{q}_{1,1} \quad \dot{q}_{2,1} \quad \dot{q}_{3,1}]^T$$

Forward velocity calculation:

$$\left.\begin{aligned} \boldsymbol{\omega}_P &= J_A{}^{-1}\left(\dot{\boldsymbol{\theta}} - J_B J_C{}^{-1}\dot{\boldsymbol{q}}\right) \\ \boldsymbol{v}_P &= J_C{}^{-1}\dot{\boldsymbol{q}} \end{aligned}\right\}$$

It is known from the equation that input motion of RMC generates pure rotational motion while input motion of TPC generates rotational motion coupled with translational motion of the output link. This means that rotational output motion is decoupled from translational motion in RPMVTP regardless of the kinematics structure of RMC. However, J_B is not zero matrix.

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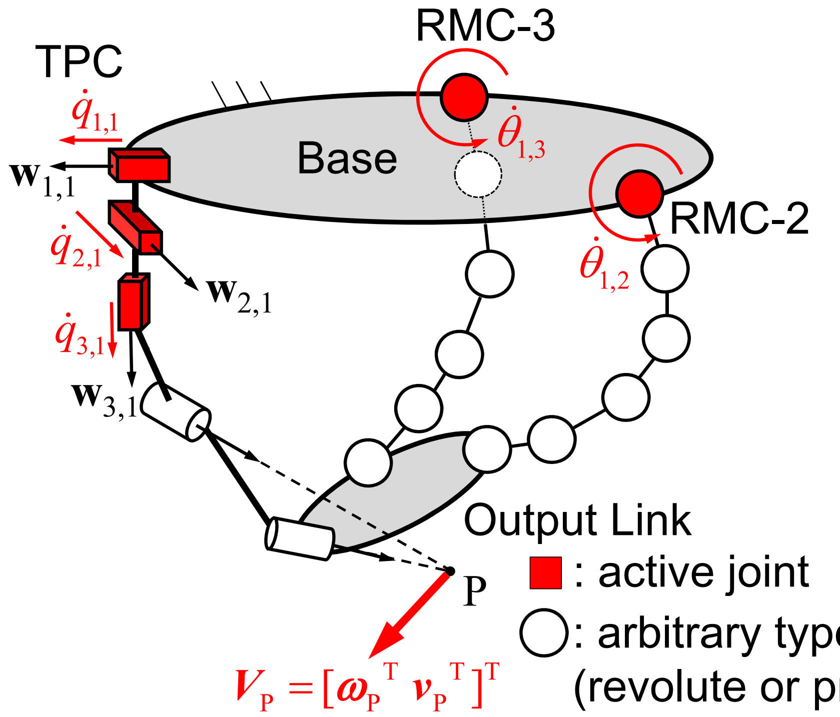
Structure of Fully decoupled RPMVTP

kinematic structure of RMC



■ : active joint

○: arbitrary type of joint (revolute or prismatic)

Input-output relationship:

$$J_T \begin{bmatrix} \boldsymbol{\omega}_P \\ \boldsymbol{v}_P \end{bmatrix} = \begin{bmatrix} J_A & 0 \\ 0 & J_C \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega}_P \\ \boldsymbol{v}_P \end{bmatrix} = \begin{bmatrix} \dot{\boldsymbol{\theta}} \\ \dot{\boldsymbol{q}} \end{bmatrix}$$

$$\dot{\boldsymbol{\theta}} = [\dot{\theta}_{1,2} \quad \dot{\theta}_{1,3} \quad 0]^T \qquad \dot{\boldsymbol{q}} = [\dot{q}_{1,1} \quad \dot{q}_{2,1} \quad \dot{q}_{3,1}]^T$$

Forward velocity equation:

$$\left.\begin{aligned} \boldsymbol{\omega}_P &= J_A{}^{-1}\dot{\boldsymbol{\theta}} \\ \boldsymbol{v}_P &= J_C{}^{-1}\dot{\boldsymbol{q}} \end{aligned}\right\}$$

$$J_B = \begin{bmatrix} \dfrac{\hat{\boldsymbol{f}}_2{}^T}{\hat{\boldsymbol{m}}_2{}^T\hat{\boldsymbol{\omega}}_{1,2} + \hat{\boldsymbol{f}}_2{}^T\hat{\boldsymbol{v}}_{1,2}} \\ \dfrac{\hat{\boldsymbol{f}}_3{}^T}{\hat{\boldsymbol{m}}_3{}^T\hat{\boldsymbol{\omega}}_{1,3} + \hat{\boldsymbol{f}}_3{}^T\hat{\boldsymbol{v}}_{1,3}} \\ \boldsymbol{0} \end{bmatrix} = 0 \quad \Rightarrow \quad \hat{\boldsymbol{f}}_i = \boldsymbol{0}$$

Moment constraint is given by active joint of RMC

$$\det J_A \neq 0 \left(J_A = \begin{bmatrix} \dfrac{\hat{\boldsymbol{m}}_2{}^T}{\hat{\boldsymbol{m}}_2{}^T\hat{\boldsymbol{\omega}}_{1,2}} \\ \dfrac{\hat{\boldsymbol{m}}_3{}^T}{\hat{\boldsymbol{m}}_3{}^T\hat{\boldsymbol{\omega}}_{1,3}} \\ (\boldsymbol{w}_{4,1} \times \boldsymbol{w}_{5,1})^T \end{bmatrix} \right) \quad \Rightarrow \quad \hat{\boldsymbol{\omega}}_{1,i} \neq \boldsymbol{0}$$

Active joint of RMC should be a revolute joint.

Structure of Fully decoupled RPMVTP

Possible kinematic structures for RMC

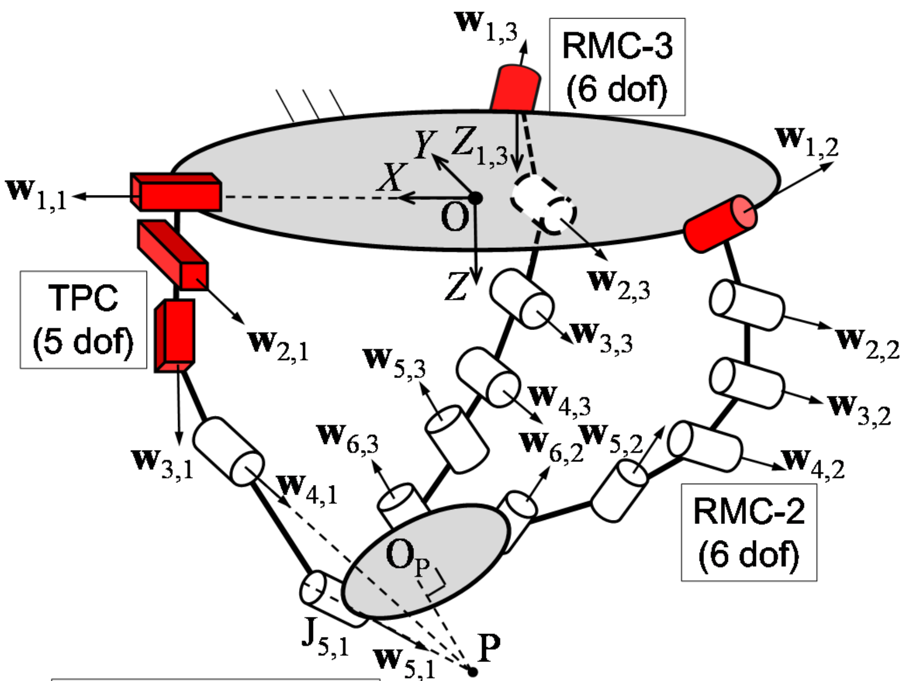
structure	structure	structure
$R_a\dot{R}\dot{R}\dot{R}\overline{RR}$	$R_a\dot{R}\dot{R}\overline{RRP}$	$R_a\dot{R}\dot{R}P\overline{RR}$
$R_a\dot{R}\dot{R}\dot{R}\overline{RP}$	$R_a\dot{R}\dot{R}\dot{R}P\overline{R}$	$R_a\dot{R}\dot{R}P\dot{R}\overline{R}$
$R_a\dot{R}P\dot{R}\dot{R}\overline{R}$	$R_aP\dot{R}\dot{R}\dot{R}\overline{R}$	$R_a\dot{R}\dot{R}\overline{R}PP$
$R_a\dot{R}\dot{R}P\overline{R}P$	$R_a\dot{R}P\dot{R}\overline{R}P$	$R_aP\dot{R}\dot{R}\overline{R}P$
$R_a\dot{R}\dot{R}PP\overline{R}$	$R_a\dot{R}P\dot{R}P\overline{R}$	$R_aP\dot{R}\dot{R}P\overline{R}$
$R_a\dot{R}PP\dot{R}\overline{R}$	$R_aPP\dot{R}\dot{R}\overline{R}$	$R_a\dot{R}\overline{R}PPP$
$R_a\dot{R}P\overline{R}PP$	$R_aP\dot{R}\overline{R}PP$	$R_a\dot{R}PP\overline{R}P$
$R_aP\dot{R}P\overline{R}P$	$R_a\dot{R}PPP\overline{R}$	$R_aP\dot{R}P\dot{R}\overline{R}$

(R_a: active revolute joint on the base)

Starting from the kinematic structures for translational parallel mechanism (TPM) with three serial connecting chains(Kim&Chung, 2003, Kong&Gosselin, 2004, Tanabe&Takeda, 2010), the kinematic structures shown above have been figured out as kinematic structures of RMC for fully decoupled SPMVTP. These have been obtained by adding a revolute joint at the base to the kinematic chains for TPM so that conditions for connecting chain of TPM are satisfied even when the added revolute joint is arbitrarily positioned.

Structure of Fully decoupled RPMVTP

An example kinematic structure of RMC



$\mathbf{w}_{1,1} \perp \mathbf{w}_{2,1} \perp \mathbf{w}_{3,1}$

$\mathbf{w}_{2,i} // \mathbf{w}_{3,i} // \mathbf{w}_{4,i}$

$\mathbf{w}_{5,i} // \mathbf{w}_{6,i}$

■ : active joint
: revolute joint
: prismatic joint

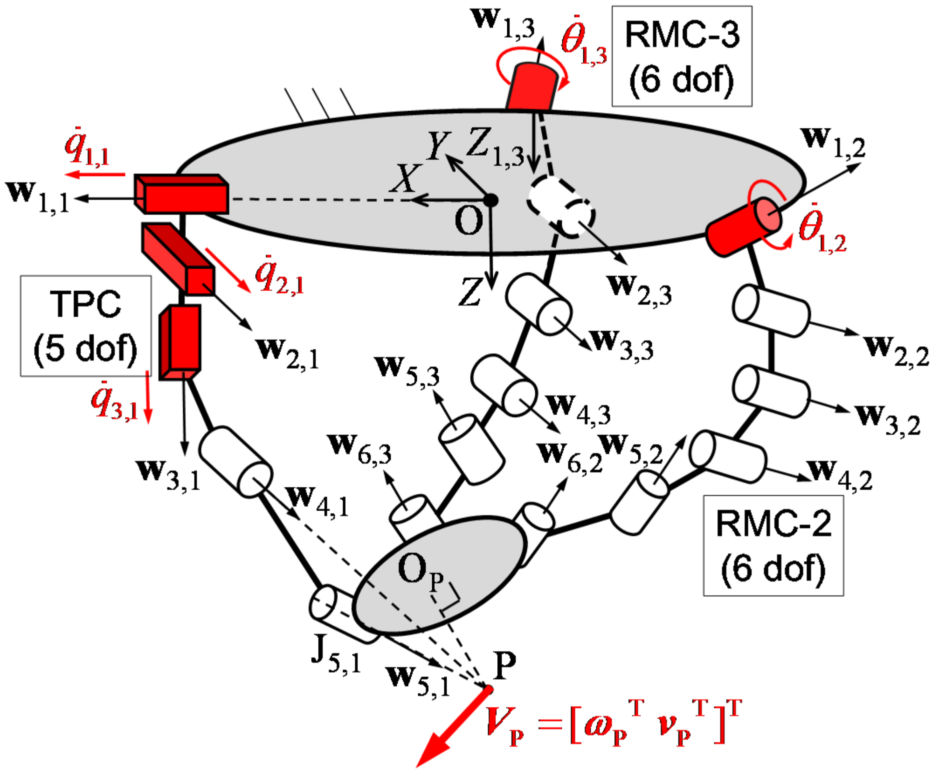
$\mathrm{PPPR_1R_1 - 2(R\dot{R}\dot{R}\dot{R}\bar{R}\bar{R})}$ mechanism

Kinematic conditions(RMC):

1. The axes of the revolute joints $\mathbf{w}_{2,i}$ to $\mathbf{w}_{4,i}$ should be parallel.
2. The axes of the revolute joints $\mathbf{w}_{5,i}$ and $\mathbf{w}_{6,i}$ should be parallel while $\mathbf{w}_{4,i}$ and $\mathbf{w}_{5,i}$ should not be parallel.
3. The axes of the revolute joints $\mathbf{w}_{1,i}$ and $\mathbf{w}_{2,i}$ should not be parallel to avoid architectural singularity of RMC.
4. Rank of the Jacobian matrix with respect to RMC as a serial chain should be 6.
5. Rank of the sub-matrix J_A should be 3.

Structure of Fully decoupled RPMVTP

An example kinematic structure of RMC



$\mathbf{w}_{1,1} \perp \mathbf{w}_{2,1} \perp \mathbf{w}_{3,1}$

$\mathbf{w}_{2,i} // \mathbf{w}_{3,i} // \mathbf{w}_{4,i}$

$\mathbf{w}_{5,i} // \mathbf{w}_{6,i}$

■ : active joint

⊂⊃ : revolute joint

▭ : prismatic joint

$\hat{m}_i$: constraint moment of RMC-i by fixing the active joint

$\mathrm{PPPR_1R_1} - 2(\mathrm{R\dot{R}\dot{R}\dot{R}\bar{R}\bar{R}})$ mechanism

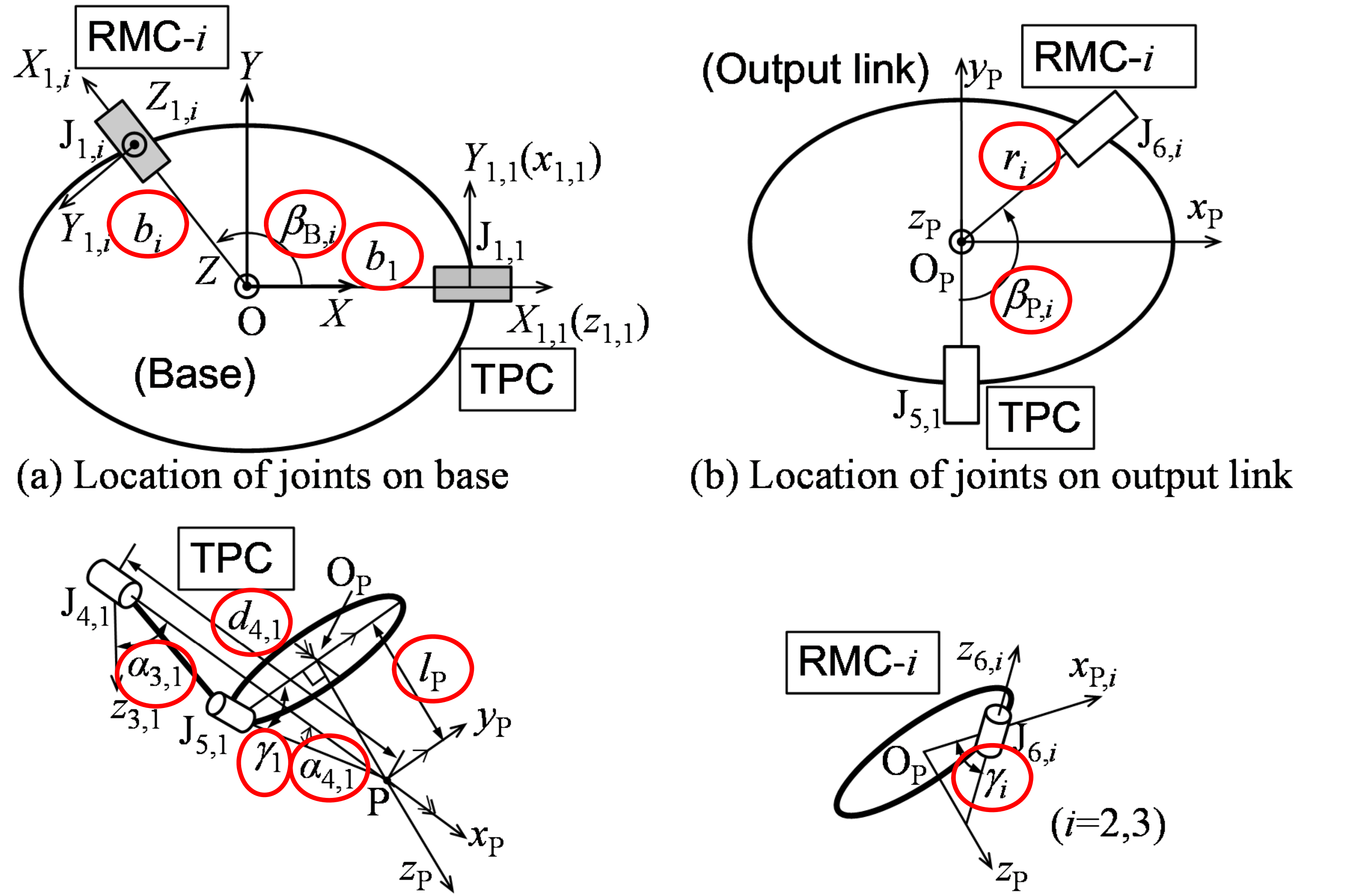
The Jacobian matrix J_T is independent of the position of the target point P while it is dependent only on the orientation of the output link.

Velocity relationship:

$$J_T \begin{bmatrix} \omega_P \\ v_P \end{bmatrix} = \begin{bmatrix} \dfrac{\hat{m}_2^T}{\hat{m}_2^T w_{1,2}} & \\ \dfrac{\hat{m}_3^T}{\hat{m}_3^T w_{1,3}} & 0_{3\times3} \\ (w_{4,1} \times w_{5,1})^T & \\ & w_{1,1}^T \\ 0_{3\times3} & w_{2,1}^T \\ & w_{3,1}^T \end{bmatrix} \begin{bmatrix} \omega_P \\ v_P \end{bmatrix} = \begin{bmatrix} \dot{\theta} \\ \dot{q} \end{bmatrix}$$

Structure of Fully decoupled RPMVTP

An example kinematic structure of RMC: kinematic constants



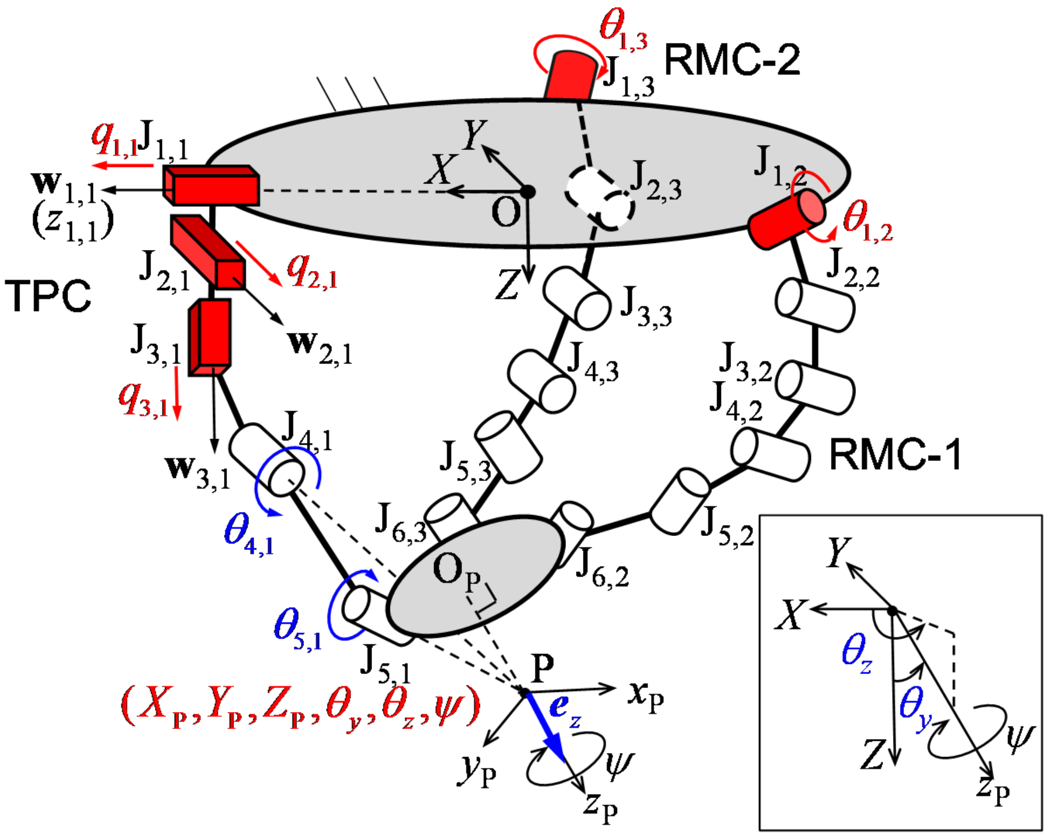
(a) Location of joints on base

(b) Location of joints on output link

(c) Location of revolute joints of TPC

(d) Location of revolute joints of RMC

Inverse displacement analysis



Kinematic structure of RPMVTP and output orientation

Transformation matrix:

$$T_P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \boldsymbol{p} & \boldsymbol{e}_x & \boldsymbol{e}_y & \boldsymbol{e}_z \end{bmatrix}$$

Output pose: 5 out of $(X_P, Y_P, Z_P, \theta_y, \theta_z, \psi)$ are independent.

Procedure:

1. From $\boldsymbol{e}_z$, $\theta_{4,1}$ and $\theta_{5,1}$ are calculated.
2. From $\boldsymbol{p}$, $q_{j,1}$ $(j=1,2,3)$ are calculated.
3. Matrix $T_{P,TPC}$ is fully determined.
4. From $T_{P,TPC}=T_P=T_{P,RMC,i}$, $\theta_{1,i}(i=2,3)$ are obtained.

In total, 8 real solutions exist for inverse displacement analysis of the mechanism.

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Numerical example

Kinematic constants of the mechanism used in simulation

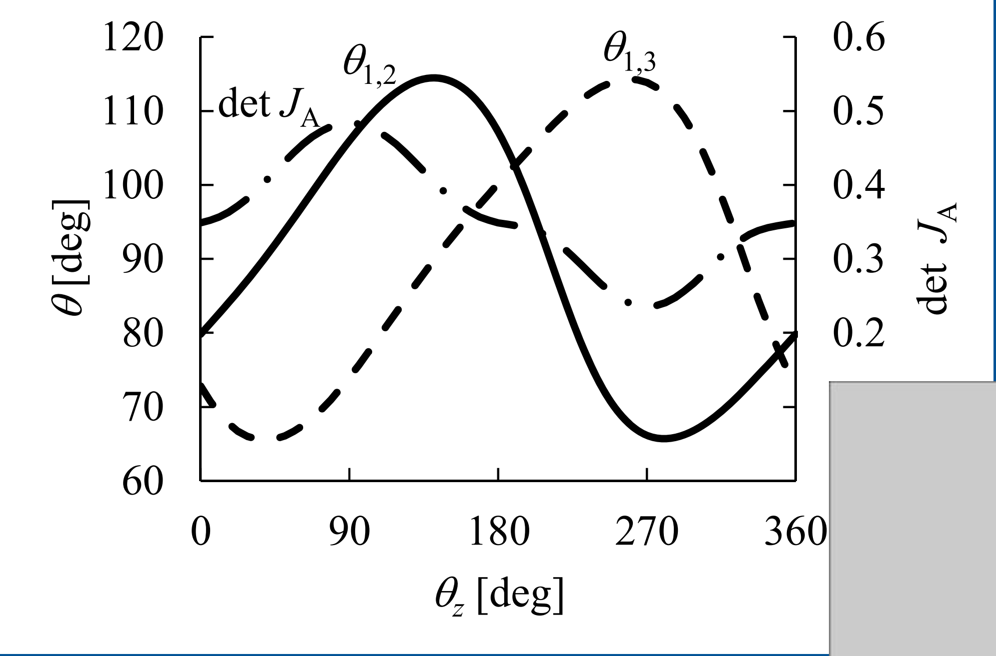
Symbols	Values	Symbols	Values	Symbols	Values
l_P	6.84 mm	$\beta_{B,3}$	135°	$d_{1,i}$	50 mm
b_1	60 mm	$\beta_{P,2}$	45°	$a_{2,i}$	50 mm
$\alpha_{3,1}$	90°	$\beta_{P,3}$	225°	$a_{3,i}$	60 mm
$d_{4,1}$	60 mm	b_i	110 mm	$a_{4,i}$	10 mm
$\alpha_{4,1}$	90°	$\alpha_{0,i}$	45°	$a_{5,i}$	40 mm
γ_1	20°	$\theta_{0,i}$	270°	γ_i	30°
$\beta_{B,2}$	135°	$a_{1,i}$	0 mm	r_i	35 mm

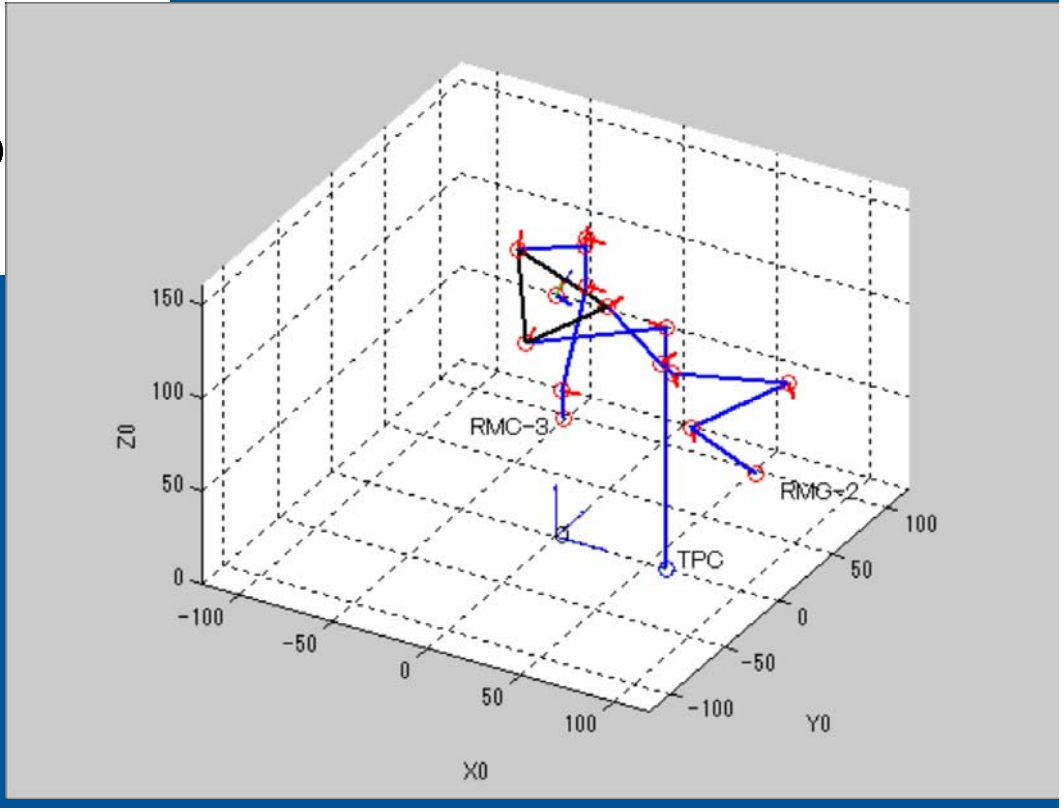
Output motions:

1. $(X_P, Y_P, Z_P) = (0, 0, 130)[\mathrm{mm}],\ \theta_y = 30^\circ, \theta_z = [0 : 360^\circ]$
2. $X_P = [-20 : 20][\mathrm{mm}], (Y_P, Z_P) = (0, 130)[\mathrm{mm}],\ \theta_y = 30^\circ, \theta_z = 0$

Numerical example

Case 1: $(X_P, Y_P, Z_P) = (0,0,130)[\text{mm}],\ \theta_y = 30^\circ, \theta_z = [0:360^\circ]$

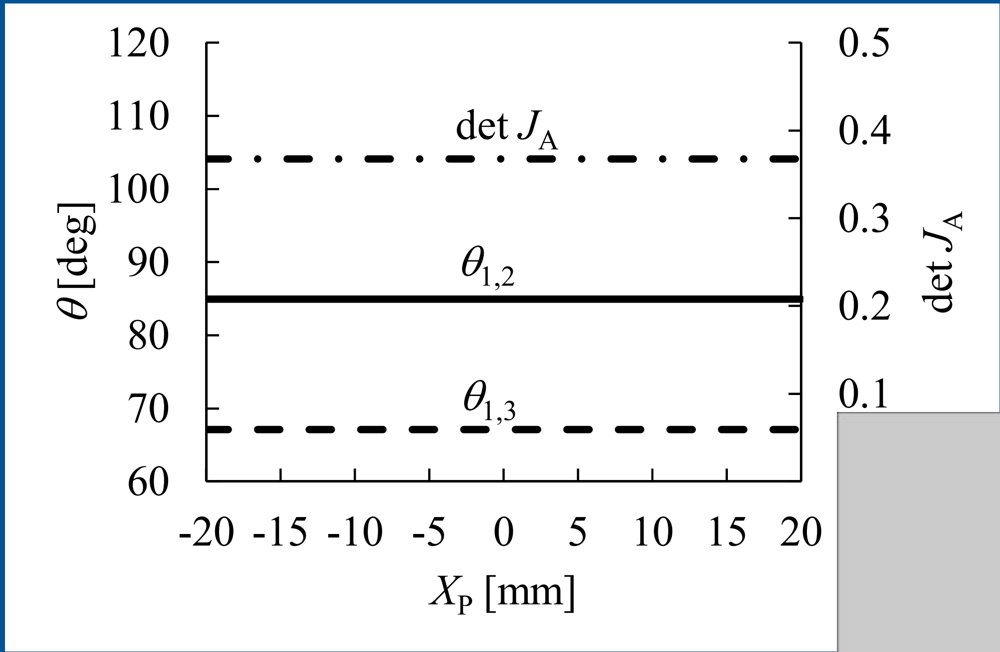


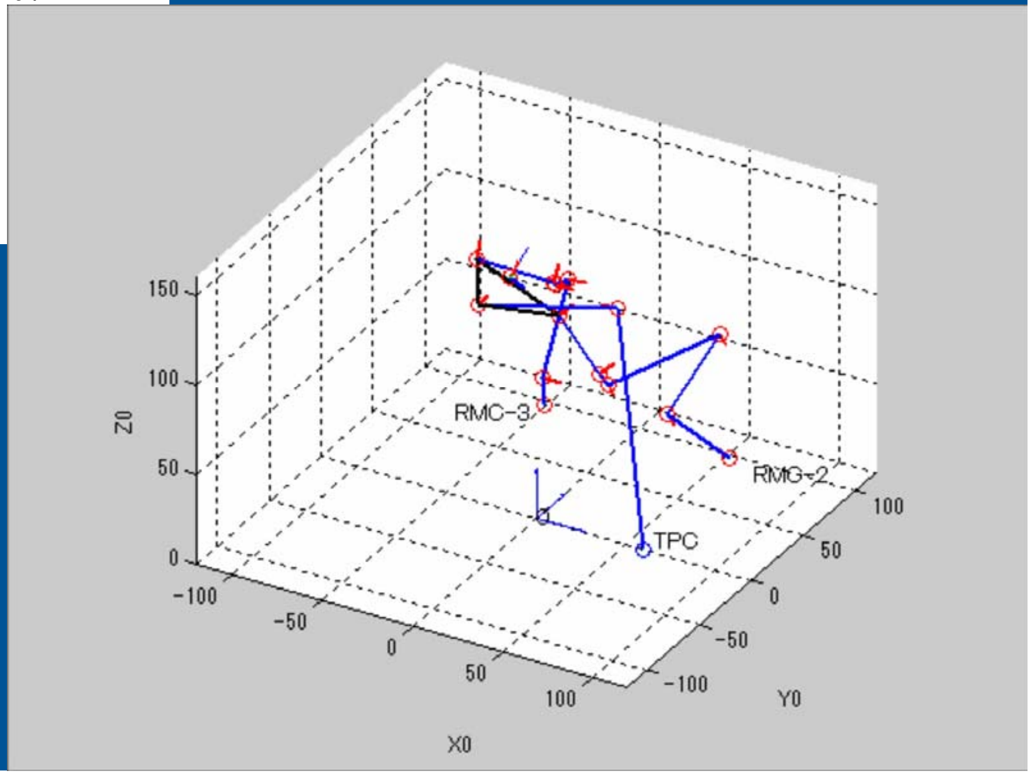


Pure rotational output motion while keeping the target point at a fixed position is achieved by input motions of RMCs without encountering singular point.

Numerical example

Case 2: $X_P = [-20:20][\text{mm}], (Y_P, Z_P) = (0, 130)[\text{mm}],\ \theta_y = 30^\circ, \theta_z = 0$





Translational output motion is achieved by input motion of TPC while keeping J_A a constant matrix (as well as det J_A).

Conclusions-RPMVTP

In the present paper, asymmetrical five-DOF fully-decoupled parallel mechanism has been figured out and its kinematic study has been carried out.
Our conclusions are summarized as follows.

1. 24 kinematic structures of fully-decoupled asymmetrical spherical parallel mechanism with variable target point, which is composed of a target point controlling chain and two rotational motion generating chains, have been figured out.
2. Taking one structure among the 24 structures in 1, a procedure for inverse displacement analysis has been clarified. It has been also clarified that input-output relationship in velocity is independent of the position of the target point.
3. Effectiveness of the mechanism has been confirmed through a numerical example of inverse displacement analysis with a check of singularity.

Conclusions

Concept of “Compensatability” of parallel manipulators:

1. Redundancy (combination of gross and fine motions)
2. Decoupled structure for simplicity
3. Optimal design based on Sensitivity

A family of “Compensatable Parallel Manipulators”:

1. A parallel manipulator with redundant actuators for gross and fine motions
2. A 3-URU pure rotational parallel manipulator with large workspace and less sensitivity to position error
3. A translational parallel manipulator with fine adjustment of orientation error
4. A rotational parallel manipulator with fine adjustment of position error
5. A rotational parallel manipulator with variable target point

Methods:

1. Structural synthesis
2. Dimensional synthesis
3. Control

Validation:

1. Design, Prototyping and Test

References-Compensatable Parallel Manipulators

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