Background 0000 Proposed formulation

Illustrative example 0000000

Conclusions 0000

Optimal design of parallel manipulators based on their dynamic performance

Jagadeesh Kilaru Murali K. Karnam Saurav Agarwal Sandipan Bandyopadhyay



Department of Engineering Design Indian Institute of Technology Madras Chennai - 600 036

| Background | |
|------------|--|
| 0000 | |
| Objective | |

Objectives

- Quantification of dynamic performance of a parallel manipulator
- ▶ Optimisation of dynamic performance, using the above

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| Background ●000 | Proposed formulation | |
|--------------------|----------------------|--|
| Objective | | |

Objectives

- Quantification of dynamic performance of a parallel manipulator
- ▶ Optimisation of dynamic performance, using the above

▲□▶ <□▶ < Ξ▶ < Ξ▶ < Ξ · のQ · ·</p>

| Background | Proposed formulation | Illustrative example | Conclusions |
|------------|----------------------|----------------------|-------------|
| Objective | | | 0000 |

Better productivity

- ▶ Reduced mass of the manipulator
- Smaller actuators
- ▶ Reduced power requirements

▲□▶ ▲□▶ ▲豆▶ ▲豆▶ 三回 めんゆ

| Background o●oo | Proposed formulation | Illustrative example | Conclusions 0000 |
|--------------------|----------------------|----------------------|---------------------|
| Objective | | | |

- Better productivity
- ▶ Reduced mass of the manipulator
- Smaller actuators
- ▶ Reduced power requirements

▲□▶ ▲□▶ ▲豆▶ ▲豆▶ 三目 - 釣�?

| Background 0000 | Proposed formulation | |
|--------------------|----------------------|--|
| Objective | | |

- Better productivity
- ▶ Reduced mass of the manipulator
- Smaller actuators
- ▶ Reduced power requirements

▲□▶ ▲□▶ ▲豆▶ ▲豆▶ 三回 めんゆ

| Background 0●00 | Proposed formulation | |
|--------------------|----------------------|--|
| Objective | | |

- Better productivity
- ▶ Reduced mass of the manipulator
- Smaller actuators
- ▶ Reduced power requirements

▲□▶ ▲□▶ ▲豆▶ ▲豆▶ 三回 めんゆ

| Background | Illustrative example | |
|------------|----------------------|--|
| 0000 | | |
| Objective | | |

- ▶ Generalised Inertia Ellipsoid (Asada *et al*, 1983)
- ▶ Dynamic manipulability (Yoshikawa *et al*, 1985)
- ▶ The concept of dynamic isotropy (Ma *et al*, 1990)
- ► The dynamic capability equations for non-homogeneous task space (Bowling *et al*, 2000)
- ▶ Dynamic performance indices for 3-DoF parallel manipulators (Gregorio *et al*, 2002)
- ▶ Dynamically optimal design considering anisotropic properties like input efforts/power and task space requirements (Zhao *et al*, 2013)

▲□▶▲□▶▲■▶▲■▶ ▲□▶ ▲□▶

| Background | Illustrative example | |
|------------|----------------------|--|
| 0000 | | |
| Objective | | |

- ▶ Generalised Inertia Ellipsoid (Asada *et al*, 1983)
- ▶ Dynamic manipulability (Yoshikawa *et al*, 1985)
- ▶ The concept of dynamic isotropy (Ma *et al*, 1990)
- ► The dynamic capability equations for non-homogeneous task space (Bowling *et al*, 2000)
- ▶ Dynamic performance indices for 3-DoF parallel manipulators (Gregorio *et al*, 2002)
- ▶ Dynamically optimal design considering anisotropic properties like input efforts/power and task space requirements (Zhao *et al*, 2013)

▲□▶▲□▶▲豆▶▲豆▶ ▲□▶

| Background | Illustrative example | |
|------------|----------------------|--|
| 0000 | | |
| Objective | | |

- ▶ Generalised Inertia Ellipsoid (Asada *et al*, 1983)
- ▶ Dynamic manipulability (Yoshikawa *et al*, 1985)
- ▶ The concept of dynamic isotropy (Ma *et al*, 1990)
- ► The dynamic capability equations for non-homogeneous task space (Bowling *et al*, 2000)
- ▶ Dynamic performance indices for 3-DoF parallel manipulators (Gregorio *et al*, 2002)
- ▶ Dynamically optimal design considering anisotropic properties like input efforts/power and task space requirements (Zhao *et al*, 2013)

▲□▶ ▲□▶ ▲ => ▲ => ● <</p>

| Background | Illustrative example | |
|------------|----------------------|--|
| 0000 | | |
| Objective | | |

- ▶ Generalised Inertia Ellipsoid (Asada *et al*, 1983)
- ▶ Dynamic manipulability (Yoshikawa *et al*, 1985)
- ▶ The concept of dynamic isotropy (Ma *et al*, 1990)
- ▶ The dynamic capability equations for non-homogeneous task space (Bowling *et al*, 2000)
- ▶ Dynamic performance indices for 3-DoF parallel manipulators (Gregorio *et al*, 2002)
- ▶ Dynamically optimal design considering anisotropic properties like input efforts/power and task space requirements (Zhao *et al*, 2013)

|▲□▶||4週▶||4厘▶||4厘▶|||厘||9000

| Background | Illustrative example | |
|------------|----------------------|--|
| 0000 | | |
| Objective | | |

- ▶ Generalised Inertia Ellipsoid (Asada *et al*, 1983)
- ▶ Dynamic manipulability (Yoshikawa *et al*, 1985)
- ▶ The concept of dynamic isotropy (Ma *et al*, 1990)
- ► The dynamic capability equations for non-homogeneous task space (Bowling *et al*, 2000)
- Dynamic performance indices for 3-DoF parallel manipulators (Gregorio *et al*, 2002)
- ▶ Dynamically optimal design considering anisotropic properties like input efforts/power and task space requirements (Zhao *et al*, 2013)

| Background | Illustrative example | |
|------------|----------------------|--|
| 0000 | | |
| Objective | | |

- ▶ Generalised Inertia Ellipsoid (Asada *et al*, 1983)
- ▶ Dynamic manipulability (Yoshikawa *et al*, 1985)
- ▶ The concept of dynamic isotropy (Ma *et al*, 1990)
- ► The dynamic capability equations for non-homogeneous task space (Bowling *et al*, 2000)
- ▶ Dynamic performance indices for 3-DoF parallel manipulators (Gregorio *et al*, 2002)
- Dynamically optimal design considering anisotropic properties like input efforts/power and task space requirements (Zhao *et al*, 2013)

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

< /⊒ ► < ⊒ ►

SOC

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

▶ Intrinsic vs. extrinsic

- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- ▶ Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

- ► Intrinsic vs. extrinsic
- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- ▶ Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

- ▶ Intrinsic vs. extrinsic
- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- ▶ Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

- ▶ Intrinsic vs. extrinsic
- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

- ▶ Intrinsic vs. extrinsic
- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- ▶ Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

(ロ) (日) (日) (王) (王) (王) (100)

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

- ▶ Intrinsic vs. extrinsic
- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- ▶ Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

| Background | | |
|------------|--|--|
| 0000 | | |
| Objective | | |

- ▶ Intrinsic vs. extrinsic
- Incorporating three disparate objects M, C, G
- ▶ Local vs. global: restriction to feasible regions
- ▶ Dimensional vs. non-dimensional indices
- ▶ Homogeneous vs. non-homogeneous task space
- Computational complexities
- ▶ Actaul vs. theoretical link model

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| | Proposed formulation | Conclusions |
|----------------------|----------------------|-------------|
| | •0000 | |
| Proposed formulation | | |

New contributions:

- ▶ Combination of dimensional and non-dimensional indices
- ► Restriction to the safe working zone (SWZ): extension of local indices to global
- ▶ Intrinsic formulation motivated by physical intuitions, but validated empirically
- ▶ Applicable to non-homogeneous task space

◆□ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶ < □ ▶

| | Proposed formulation | |
|----------------------|----------------------|--|
| | 00000 | |
| Proposed formulation | | |

New contributions:

- ▶ Combination of dimensional and non-dimensional indices
- Restriction to the safe working zone (SWZ): extension of local indices to global
- ▶ Intrinsic formulation motivated by physical intuitions, but validated empirically
- ▶ Applicable to non-homogeneous task space

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| | Proposed formulation | |
|----------------------|----------------------|--|
| | 00000 | |
| Proposed formulation | | |

New contributions:

- ▶ Combination of dimensional and non-dimensional indices
- ► Restriction to the safe working zone (SWZ): extension of local indices to global
- Intrinsic formulation motivated by physical intuitions, but validated empirically
- ▶ Applicable to non-homogeneous task space

(ロ) (日) (日) (王) (王) (王) (100)

| | Proposed formulation | Conclusions |
|----------------------|----------------------|-------------|
| | •0000 | |
| Proposed formulation | | |

New contributions:

- ▶ Combination of dimensional and non-dimensional indices
- ► Restriction to the safe working zone (SWZ): extension of local indices to global
- ► Intrinsic formulation motivated by physical intuitions, but validated empirically
- ▶ Applicable to non-homogeneous task space

| | Proposed formulation | Conclusions |
|----------------------|----------------------|-------------|
| | 00000 | |
| Proposed formulation | | |

► A particle of constant mass m, moving in Rⁿ, has the simplest possible *inertia matrix*:

$$M = mI_{n \times n}, \ m \in \mathbb{R}^+$$

- The n DoF are completely *decoupled*
- ▶ The inertia is identical in *all* directions, i.e., the inertia is *isotropic*
- If the m above is *small*, then the system responds fast

▲□▶ ▲□▶ ▲豆▶ ▲豆▶ 三回 - のへで

| | Proposed formulation | Conclusions |
|----------------------|----------------------|-------------|
| | 00000 | |
| Proposed formulation | | |

► A particle of constant mass m, moving in Rⁿ, has the simplest possible *inertia matrix*:

 $\boldsymbol{M} = m \boldsymbol{I}_{n \times n}, \ m \in \mathbb{R}^+$

• The n DoF are completely decoupled

- ▶ The inertia is identical in *all* directions, i.e., the inertia is *isotropic*
- If the m above is *small*, then the system responds fast

| | Proposed formulation | | |
|----------------------|----------------------|---------|------|
| 0000 | 00000 | 0000000 | 0000 |
| Proposed formulation | | | |

► A particle of constant mass m, moving in Rⁿ, has the simplest possible *inertia matrix*:

 $\boldsymbol{M} = m \boldsymbol{I}_{n \times n}, \ m \in \mathbb{R}^+$

- The n DoF are completely *decoupled*
- ▶ The inertia is identical in *all* directions, i.e., the inertia is *isotropic*
- If the m above is *small*, then the system responds fast

▲□▶ ▲□▶ ▲□▶ ▲□▶ ▲□▶ ▲□▶ ▲□▶ ▲□▶

| | Proposed formulation | | |
|----------------------|----------------------|---------|------|
| 0000 | 00000 | 0000000 | 0000 |
| Proposed formulation | | | |

► A particle of constant mass m, moving in Rⁿ, has the simplest possible *inertia matrix*:

$$\boldsymbol{M} = m \boldsymbol{I}_{n \times n}, \ m \in \mathbb{R}^+$$

- The n DoF are completely *decoupled*
- ▶ The inertia is identical in *all* directions, i.e., the inertia is *isotropic*
- If the m above is *small*, then the system responds fast

| | Proposed formulation | Conclusions |
|----------------------|----------------------|-------------|
| | 00000 | |
| Proposed formulation | | |

Local indices : intrinsic measures for n-DOF system

► Index µ₁ (dynamic isotropy index) is formulated to measure isotropy of mass matrix (M) as,

$$\mu_1(\boldsymbol{M}) = \frac{n^2}{\kappa(\boldsymbol{M})}, \quad 0 \le \mu_1(\boldsymbol{M}) \le 1$$

where, $\kappa(\boldsymbol{M}) = \left(\frac{1}{\lambda_1} + \dots + \frac{1}{\lambda_n}\right) (\lambda_1 + \dots + \lambda_n).$

• Index μ_2 (inertia index) is formulated to measure the maximum inertia using M as,

$$\mu_2(\boldsymbol{M}) = \max_i \{\lambda_i(\boldsymbol{M})\}, \ i = 1, \dots, n.$$

・ロ> < 団> < 豆> < 豆> < 豆> < 豆

| | Proposed formulation | |
|----------------------|----------------------|--|
| | 00000 | |
| Proposed formulation | | |

Local indices : intrinsic measures for n-DOF system

► Index µ₁ (dynamic isotropy index) is formulated to measure isotropy of mass matrix (M) as,

$$\mu_1(\boldsymbol{M}) = \frac{n^2}{\kappa(\boldsymbol{M})}, \quad 0 \le \mu_1(\boldsymbol{M}) \le 1$$

where, $\kappa(\boldsymbol{M}) = \left(\frac{1}{\lambda_1} + \dots + \frac{1}{\lambda_n}\right) (\lambda_1 + \dots + \lambda_n).$

 Index µ₂ (inertia index) is formulated to measure the maximum inertia using *M* as,

$$\mu_2(\boldsymbol{M}) = \max_i \{\lambda_i(\boldsymbol{M})\}, \ i = 1, \dots, n.$$

▲□▶ ▲ □ ▶ ▲ □ ▶

Sac

| | Proposed formulation | |
|----------------------|----------------------|--|
| | 00000 | |
| Proposed formulation | | |

Global indices : intrinsic measures for n-DoF system

Local indices are extended to global indices over a subset of the workspace, such as the SWZ:

► Global isotropy index:

$$\bar{\mu}_1(\boldsymbol{M}) = \frac{\int_V \mu_1(\boldsymbol{M}) dv}{\int_V dv}$$

▶ Global inertia index:

$$ar{\mu}_2(oldsymbol{M}) = \max_V(\mu_2(oldsymbol{M})) = \max_V\left(\max_i\{\lambda_i(oldsymbol{M})\}
ight)$$

A B > A B >

Sac

| | Proposed formulation | |
|----------------------|----------------------|--|
| | 00000 | |
| Proposed formulation | | |

Global indices : intrinsic measures for n-DoF system

Local indices are extended to global indices over a subset of the workspace, such as the SWZ:

► Global isotropy index:

$$\bar{\mu}_1(\boldsymbol{M}) = \frac{\int_V \mu_1(\boldsymbol{M}) dv}{\int_V dv}$$

▶ Global inertia index:

$$ar{\mu}_2(oldsymbol{M}) = \max_V(\mu_2(oldsymbol{M})) = \max_V\left(\max_i\{\lambda_i(oldsymbol{M})\}
ight)$$

+ 3 + 4 3 +

Sac

| Background | Proposed formulation | Illustrative example | |
|----------------------|----------------------|----------------------|--|
| | 00000 | | |
| Proposed formulation | | | |

Formulation of the optimisation problem

$$\begin{array}{l} \text{Minimise} \begin{cases} f_1(\boldsymbol{x}) = -\bar{\mu}_1 \\ f_2(\boldsymbol{x}) = \bar{\mu}_2 \end{cases} \\ \text{subject to: } g_i(\boldsymbol{x}) \leq 0, \\ x_j \in [a_j, b_j], \quad j = 1, \dots, m. \end{cases}$$

- ▲口▶ ▲母▶ ▲臣▶ ▲臣▶ 三 のへで

ground Proposed formulation 00000 Illustrative example •000000 Conclusions 0000

Sar

3-RRR planar parallel manipulator (PPM)

3-RRR planar parallel manipulator (PPM)



Kinematic details of 3-<u>R</u>RR planar parallel manipulator (PPM)



Commercial prototype developed at Systemantics India Pvt. Ltd.

(日本)

| | | Illustrative example | |
|--------------------------|------------------|----------------------|--|
| | | 000000 | |
| 3-RRR planar parallel ma | anipulator (PPM) | | |

Link modelling





◆□ ▶ <□ ▶ < Ξ ▶ < Ξ ▶ ○ 2 ○ ○ </p>

 Background
 Proposed formulation
 Illustrative example
 Conclusions

 0000
 0000
 0000
 0000

 3-RRR planar parallel manipulator (PPM)
 Conclusions
 0000

Results: Pareto front



Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

Sac

| | | Illustrative example | |
|--------------------------|------------------|----------------------|--|
| | | 000000 | |
| 3-RRR planar parallel ma | anipulator (PPM) | | |

Comparison of designs from Pareto plot and existing design

| Design | $\bar{\mu}_1$ | $\bar{\mu}_2$ | $\tau_p(\text{Nm})$ | $	au_p(\mathrm{Nm})$ |
|----------|---------------|---------------|---------------------|----------------------|
| point | | $(kg-m^2)$ | u = 1 m/s | u = 1.5 m/s |
| a | 0.58 | 0.12 | 8.30 | 19.08 |
| b | 0.78 | 0.17 | 9.20 | 19.92 |
| с | 0.84 | 0.43 | 12.33 | 27.74 |
| Existing | 0.48 | 1.19 | 16.48 | 37.67 |

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras.

< <p>I

▲ @ ▶ ▲ ■ ▶

- ∢ ⊒ ▶

Sac

Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

 Background
 Proposed formulation
 Illustrative example
 Conclusions

 0000
 0000
 0000
 0000
 0000

 3-RRR planar parallel manipulator (PPM)
 Conclusions
 0000
 0000

Validation via inverse dynamic simulations



Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

Sac

| | | Illustrative example | |
|--------------------------|------------------|----------------------|------|
| 0000 | 00000 | 0000000 | 0000 |
| 3-RRR planar parallel ma | anipulator (PPM) | | |

Torque plots: u = 1.0 m/s



| Background | Proposed formulation | Illustrative example | |
|---|----------------------|----------------------|--|
| 0000 | 00000 | 000000● | |
| 3-RRR planar parallel manipulator (PPM) | | | |

Torque plots: u = 1.5 m/s



| Background 0000 | Proposed formulation | Conclusions •000 |
|--------------------|----------------------|---------------------|
| Conclusions | | |

Discussions: advantages

- Intrinsic indices are used for global enhancement of performance, which seem to agree with extrinsic results
- ▶ Dimensional inhomogenity is taken care of, to a large extent
- ▶ No further validation is required, as the analysis is confined to the SWZ

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

Sar

∢ ⊒ ▶

| Background 0000 | Proposed formulation | Conclusions •000 |
|--------------------|----------------------|---------------------|
| Conclusions | | |

Discussions: advantages

- ▶ Intrinsic indices are used for global enhancement of performance, which seem to agree with extrinsic results
- Dimensional inhomogenity is taken care of, to a large extent
- ▶ No further validation is required, as the analysis is confined to the SWZ

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

434434

Sar

| Background | Proposed formulation | Conclusions |
|-------------|----------------------|-------------|
| 0000 | 00000 | •000 |
| Conclusions | | |

Discussions: advantages

- ▶ Intrinsic indices are used for global enhancement of performance, which seem to agree with extrinsic results
- ▶ Dimensional inhomogenity is taken care of, to a large extent
- No further validation is required, as the analysis is confined to the SWZ

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

Sar

4 B b

| Background 0000 | Proposed formulation | $ \begin{array}{c} Conclusions \\ 0 \bullet 00 \end{array} $ |
|--------------------|----------------------|--|
| Conclusions | | |

Discussions: disadvantages/limitations

Computationally intensive for large degree-of-freedom systems

- ▶ Considers only the inertia terms, and not the potential ones
- ▶ May suffer from dimensional inhomogenity, in cases where actuators are of mixed type

▲□▶ ▲□▶ ▲豆▶ ▲豆▶ 豆 りへで

| Background 0000 | Proposed formulation 00000 | $ \begin{array}{c} {\rm Conclusions} \\ {\rm 0}{\scriptstyle \bullet}{\rm 00} \end{array} $ |
|--------------------|-------------------------------|---|
| Conclusions | | |

Discussions: disadvantages/limitations

- Computationally intensive for large degree-of-freedom systems
- ▶ Considers only the inertia terms, and not the potential ones
- ► May suffer from dimensional inhomogenity, in cases where actuators are of mixed type

- • □ • • @ • • 至 • • 至 • 至 • の • @

| Background 0000 | Proposed formulation | Conclusions o●oo |
|--------------------|----------------------|---------------------|
| Conclusions | | |

Discussions: disadvantages/limitations

- Computationally intensive for large degree-of-freedom systems
- ▶ Considers only the inertia terms, and not the potential ones
- ▶ May suffer from dimensional inhomogenity, in cases where actuators are of mixed type

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

▲ 御 ▶ ▲ 国 ▶ ▲ 国 ♪

Sar

| Background 0000 | Proposed formulation | Conclusions 0000 |
|--------------------|----------------------|---------------------|
| Conclusions | | |

Thank you for your attention!

Questions/comments?

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

Sar

| Background 0000 | Proposed formulation | Conclusions 000● |
|--------------------|----------------------|---------------------|
| Conclusions | | |

Sample results: design point a

| Design | Existing | Design |
|------------------------|----------|----------|
| | Design | point: a |
| l (mm) | 500 | 307 |
| $r (\mathrm{mm})$ | 500 | 500 |
| a (mm) | 150 | 136 |
| b (mm) | 1000 | 938 |
| $\alpha_{mid} \ (deg)$ | 68 | 62 |

Sandipan Bandyopadhyay, Department of Engineering Design, Indian Institute of Technology Madras. Optimal design of parallel manipulators based on their dynamic performance [IFToMM World Congress, 2015]

(日) (同) (日) (日)

JAG.