Exploiting Dynamics Singularities for Increasing the Robot Capabilities

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Introduction

Dynamics singularities

Appear when the system of wrenches applied on the mechanism under control loses its rank (locally) and is no more able to sustain the efforts applied on the mechanism

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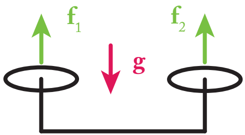
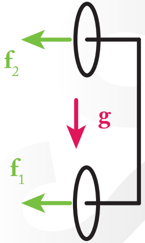
Singularities of the dynamics appear in many systems

- UAVs, ROVs





dynamics singularity

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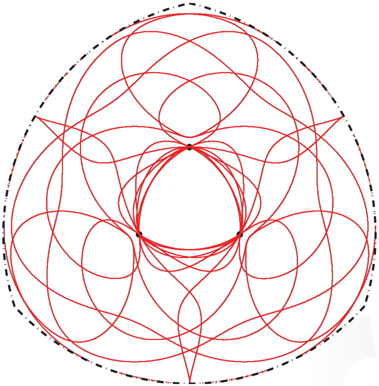
- UAVs, ROVs
- Parallel robots

Type 2 (parallel) singularities of *PKM*

Probably, most important drawback of PKM ⇒ Type 2 singularities



Singularities of a 3–RRR planar robot [Bonev 2001]

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- Redundancy
- Design of robots with variable actuation modes
- Working mode or Assembly mode changing

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- Working mode or **Assembly mode changing**

Assembly mode changing (AMC)

Two main methods

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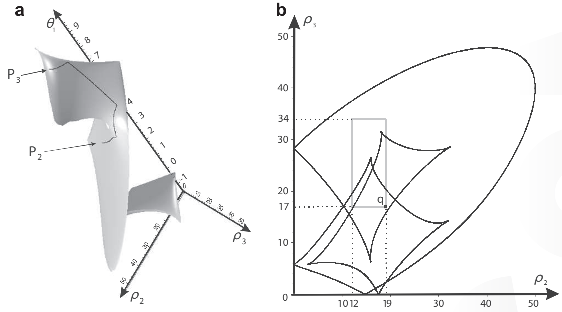
- Non-singular AMC: Encircling a cusp point

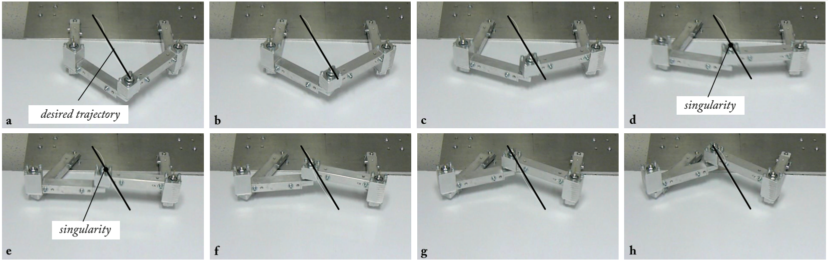


[Zein et al. MMT 2008]

Assembly mode changing (AMC)

Two main methods

- Non-singular AMC: Encircling a cusp point
- Singular AMC: Trajectories respecting a dynamic criterion



[Briot et al. MUBO 2015]

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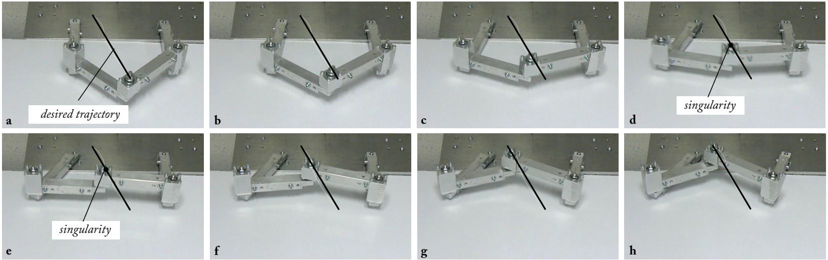
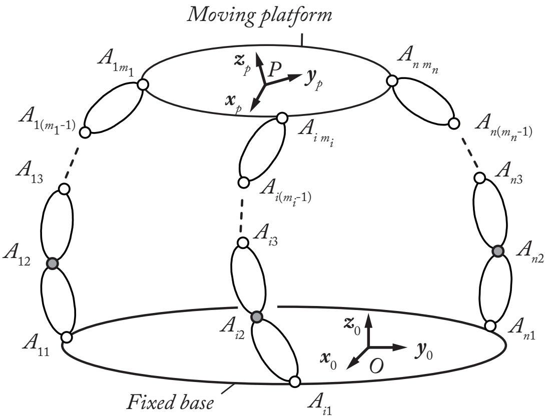


[Briot et al. MUBO 2015]

Inverse dynamic model of *PKM*

A general parallel robot



Inverse dynamic model of *PKM*

A general parallel robot

Three sets of variables:

- active joint coordinates and velocities: $\mathbf{q}_a$ and $\dot{\mathbf{q}}_a$
- passive joint coordinates and velocities: $\mathbf{q}_d$ and $\dot{\mathbf{q}}_d$
- platform coordinates and twist: $\mathbf{x}$ and ${}^0\mathbf{t}_r$ (!! $\dot{\mathbf{x}} \neq {}^0\mathbf{t}_r$)

Inverse dynamic model of *PKM*

Starting from the loop-closure equations [Briot and Khalil 2015]

$$\mathbf{h}_r(\mathbf{x}, \mathbf{q}_a) = \mathbf{0} \Rightarrow \mathbf{A}_r{}^0\mathbf{t}_r + \mathbf{B}\dot{\mathbf{q}}_a = \mathbf{0} \tag{1}$$

$$\mathbf{h}_t(\mathbf{x}, \mathbf{q}_a, \mathbf{q}_d) = \mathbf{0} \Rightarrow \mathbf{J}_t{}^0\mathbf{t}_r - \mathbf{J}_{ta}\dot{\mathbf{q}}_a = \mathbf{J}_{td}\dot{\mathbf{q}}_d \tag{2}$$

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And using the Lagrange equations with multipliers, we get

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{ta} + \mathbf{J}^{T\,0}\mathbf{w}_r + \mathbf{J}_d^T \boldsymbol{\tau}_{td} \quad (3)$$

- $\boldsymbol{\tau}$ is the $(n_a \times 1)$ vector of the real robot input efforts
- $\boldsymbol{\tau}_{ta,td} = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\mathbf{q}}_{a,d}}\right)^T - \left(\frac{\partial L}{\partial \mathbf{q}_{a,d}}\right)^T$ in which L is the Lagrangian

Recalls on the inverse dynamic model of *PKM*

And

- ${}^{0}\mathbf{w}_r$ is the reaction wrench of the platform when considered freely moving

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- the matrix $\mathbf{J} = -\mathbf{A}_r^{-1}\mathbf{B}$ is the robot kinematic Jacobian matrix

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Thus

$$\tau = \tau_{ta} - \mathbf{B}^T\mathbf{A}_r^{-T\,0}\mathbf{w}_r - (\mathbf{B}^T\mathbf{A}_r^{-T}\mathbf{J}_t^T + \mathbf{J}_{ta}^T)\mathbf{J}_{td}^{-T}\tau_{td} \qquad (5)$$

Degeneracy of the inverse dynamic model of *PKM*

As a result

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Thus

- if $\det(\mathbf{A}_r) = 0$: Type 2 singularities!
- if $\det(\mathbf{J}_{td}) = 0$: LPJTS singularities!

Recalls

What is a Type 2 singularity?

Recalls

What is a Type 2 singularity?

- A degeneracy condition of the I/O first-order kinematic model

$$\mathbf{A}_r{}^0\mathbf{t}_r + \mathbf{B}\dot{\mathbf{q}}_a = \mathbf{0} \tag{6}$$

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What is a Type 2 singularity?

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$$\mathbf{A}_r{}^0\mathbf{t}_r + \mathbf{B}\dot{\mathbf{q}}_a = \mathbf{0} \tag{6}$$

- If $\mathbf{A}_r$ is rank-deficient, a twist $\mathbf{t}_s \neq \mathbf{0}$ exists such that

$$\mathbf{A}_r\,\mathbf{t}_s = 0 \Leftrightarrow \mathbf{t}_s^T\,\mathbf{A}_r^T = 0 \tag{7}$$

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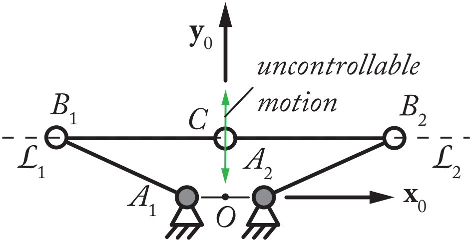
- $\mathbf{t}_s$ defines the gained motion inside the Type 2 singularity

Recalls

Example of Type 2 singularity



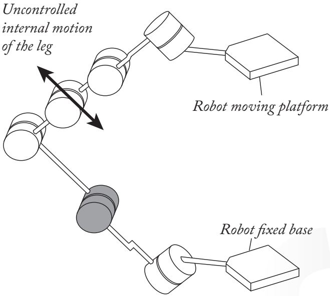
Recalls

What is a LPJTS singularity?

Recalls

What is a LPJTS singularity?

- LPJTS singularity = Leg passive joint twist system singularity



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$\Rightarrow$ Impossible to cross Type 2 and LPJTS singularities

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$\Rightarrow$ Impossible to cross Type 2 and LPJTS singularities

BUT THAT IS NOT TRUE!

Crossing Type 2 singularities

Starting from the Lagrange equations

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{ta} - \mathbf{B}^T \boldsymbol{\lambda}_1 - \mathbf{J}_{ta}^T \boldsymbol{\lambda}_2 \quad (8)$$

$$^0\mathbf{w}_r = \mathbf{A}_r^T \boldsymbol{\lambda}_1 - \mathbf{J}_t^T \boldsymbol{\lambda}_2 \quad (9)$$

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Assuming that $\det(\mathbf{J}_{td}) \neq 0$

$$\boldsymbol{\lambda}_2 = \mathbf{J}_{td}^{-T} \boldsymbol{\tau}_{td} \tag{11}$$

Crossing Type 2 singularities

Introducing (11) into (9)

$$\mathbf{A}_r^T \lambda_1 = \mathbf{w}_p \qquad (12)$$

where $\mathbf{w}_p = {}^0\mathbf{w}_r + \mathbf{J}_t^T \mathbf{J}_{td}^{-T} \tau_{td}$

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- A non null vector λ_1 corresponding to a null value of $\mathbf{w}_p$ can exist.
- There is an infinity of solutions for λ_1 and that the robot platform is not in equilibrium.

Degeneracy due to the matrix $\mathbf{A}_r$

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- Left-multiplying $\mathbf{A}_r^T \lambda_1 = \mathbf{w}_p$ by $\mathbf{t}_s^T$

$$\mathbf{t}_s^T\,\mathbf{A}_r^T \lambda_2 = 0 \Rightarrow \mathbf{t}_s^T\,\mathbf{w}_p = 0$$

Degeneracy due to the matrix $\mathbf{A}_r$

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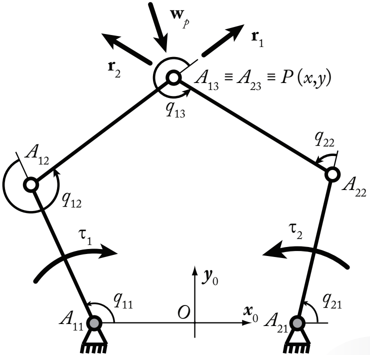
- $\mathbf{w}_p$ is a function of $\mathbf{x}$, ${}^0\mathbf{t}_r$ and ${}^0\dot{\mathbf{t}}_r$, so an optimal trajectory planning can be used to respect the criterion
- In order to avoid infinite input efforts while crossing a Type 2 singularity, the sum of the wrenches applied on the platform by the legs, inertia/gravitational effects and external environment must be reciprocal to the uncontrollable motion of the platform inside the singularity (in other words, the power of these wrenches along the platform uncontrollable motion must be null).

Degeneracy due to the matrix $\mathbf{A}_r$

An illustrative example

A five-bar mechanism in a general configuration

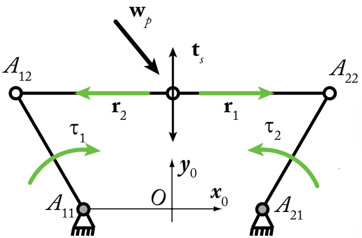


Static equilibre iff $\mathbf{w}_p = \mathbf{r}_1 + \mathbf{r}_2$

Degeneracy due to the matrix $\mathbf{A}_r$

An illustrative example

In a Type 2 singularity



$\mathbf{w}_p = \mathbf{r}_1 + \mathbf{r}_2$ with

- $\mathbf{r}_1 \times \mathbf{r}_2 = \mathbf{0}$
- $\mathbf{t}_s^T \mathbf{r}_1 = \mathbf{t}_s^T \mathbf{r}_2 = 0$ ($\mathbf{t}_s$ uncontroll. motion)

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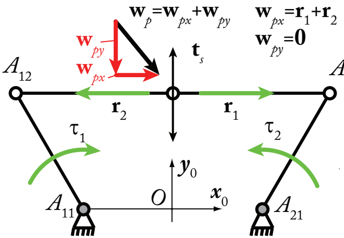

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Problem if $\mathbf{t}_s^T \mathbf{w}_p \neq 0$

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An illustrative example

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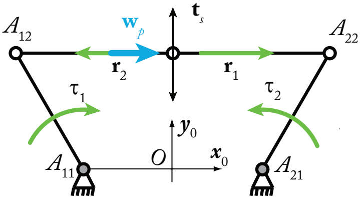

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No problem if $\mathbf{t}_s^T \mathbf{w}_p = 0$

LPJTS singularities

Possibility also to cross LPJTS singularities

But not detailed here (see [Briot et al. 2016 MUBO])

Increasing the robot workspace

Trajectories through Type 2 singularities

Request to respect the criterion $\mathbf{t}_s^T \mathbf{w}_p = 0$ when the robot is in singularity

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Note that:

- $\mathbf{t}_s$ depends on the robot configuration
- $\mathbf{w}_p$ depends on the robot configuration, velocity and acceleration

Increasing the robot workspace

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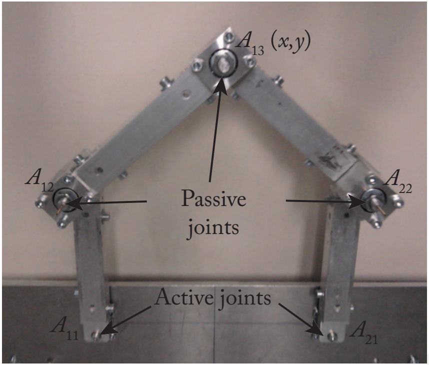

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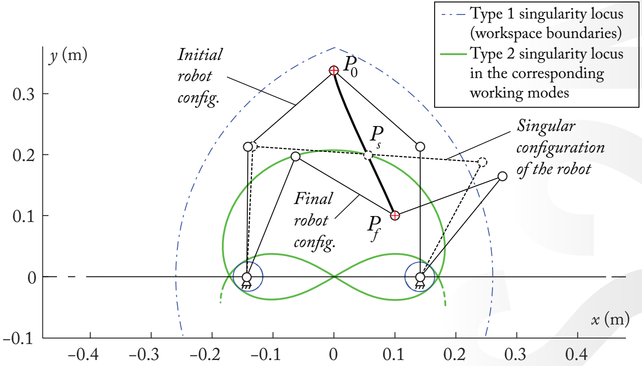

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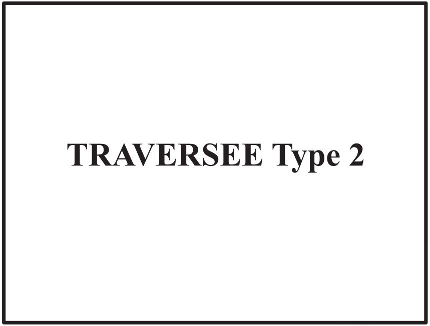

Criterion is not respected

Increasing the robot workspace

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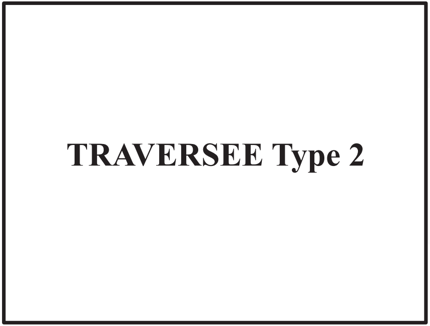
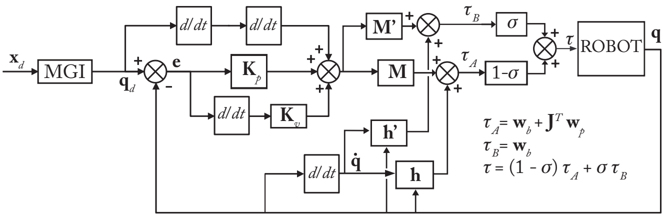


Criterion is respected

Practical implementation

Robustness issues

Multimodel controller with adaptive term [Pagis et al. 2015]



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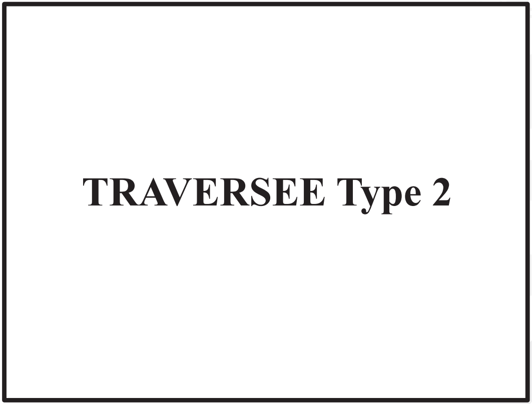
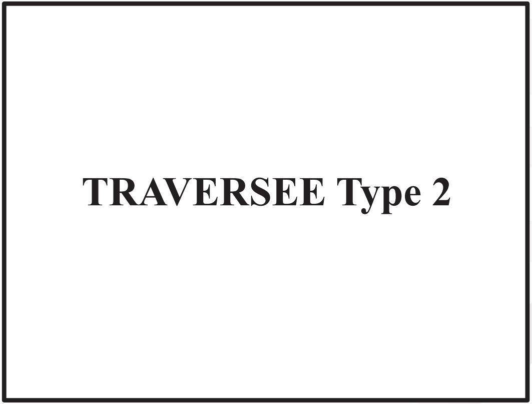


Similar approach for crossing dynamics singularities of drones

Not our works! [Castillo et al, 2016]



Design and control of a dynamically reconfigurable aerial parallel robot

Aerial parallel robots

Since 2012, large development of aerial robotics

- Serial robot mounted on the drone
- Aerial cable robot

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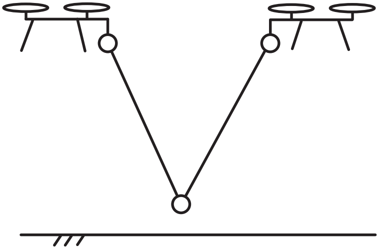
Why aerial parallel robots?

- The efforts applied on the tool are spread over the drones, enhancing the total payload
- The absence of additional embedded motors to actuate the effector reduces the load of the system itself and maintain the energetic autonomy of the drones
- The large choice of leg topology leading to a variety of physical properties of potential interest
- To deport actuators from the end-effector (no wind perturbation during inspection)

Aerial parallel robots

Why dynamically reconfigurable aerial parallel robots?

Reconfiguration for landing on the ground



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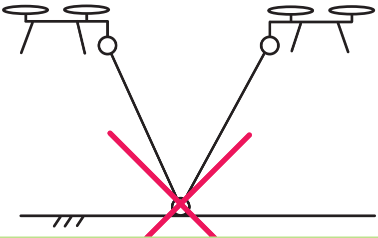

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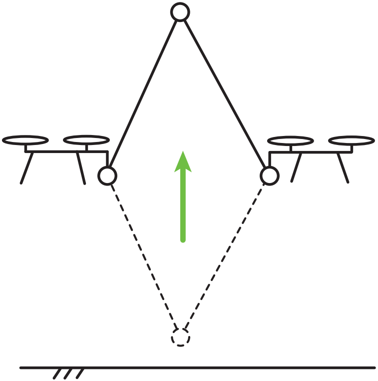
Why dynamically reconfigurable aerial parallel robots?

Reconfiguration for landing on the ground



Aerial parallel robots

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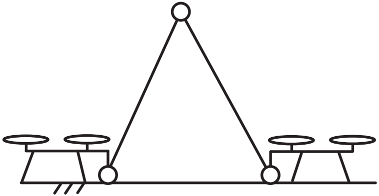
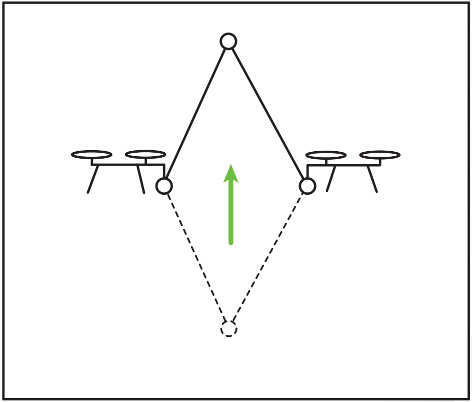


Aerial parallel robots

Why dynamically reconfigurable aerial parallel robots?

Reconfiguration for accessing larger aeras in constrained environment



Aerial parallel robots

First results

- Definition of a controller for trajectory tracking
- Dynamics modelling and dynamics parameter identification
- First experimentations

Aerial parallel robots

First results

TRAVERSEE Type 2

Aerial parallel robots

To come

- Experimentations with the two drones
- Dynamic reconfigurability
- Feedback on design (6 DOF, simpler controller, etc.)

Concluding remarks

Exploiting dynamics singularities?

Very usefull for enlarging the workspace size of parallel robots

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Crossing LPJTS singularities?

Possible, but not presented here

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Requires also a specific controller

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What you have shown is transposable to other mechanisms like drones

Concluding remarks

Colleagues




Students