Università di Genova - DIST
GRAAL- **G**enoa **R**obotic **A**nd **A**utomation **L**ab

Modular Control Architectures

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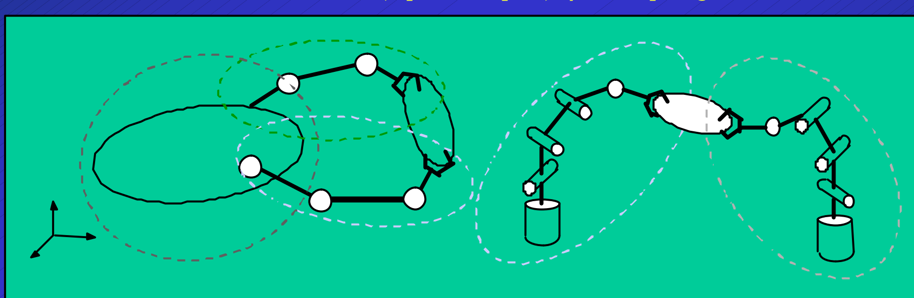
Multirobot System

•***Multirobot System:*** *A structure is considered to be a Multirobot System when it is seen as the composition of different "Basic Robotic Units" each one characterized by its own controlled capabilities*

Task execution by part of a Multirobot System necessarily requires the Coordination (explicit or implicit) of the composing ro botic units



Outline

- Single Arms and Vehicles
  - Non defective single arm
  - Defective single arm
  - Non-holonomic vehicle
- Serial Composition of systems
  - Decentralized Control scheme
  - Convergence and stability issues
  - Examples and Simulation results
- Branched Composition of systems
  - Object Manipulation
  - Examples

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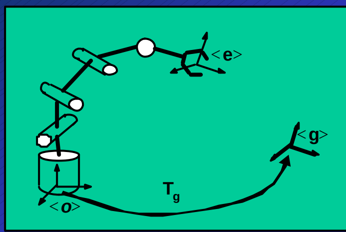
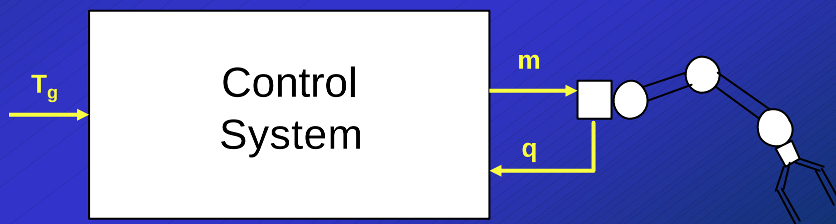
Non Defective Single Arm: Position Task

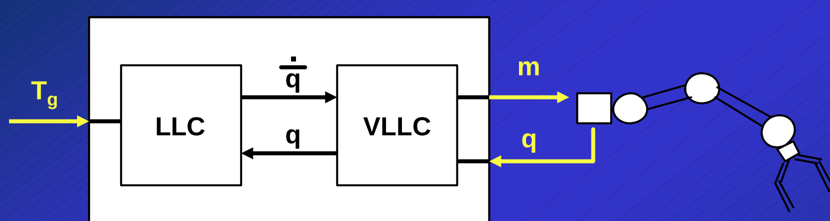


Task objective

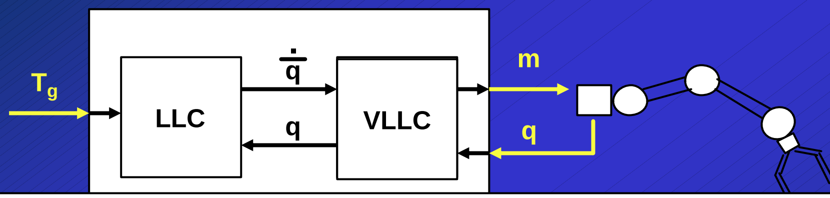
To design a control system to drive the end-effector frame <e> toward the goal frame <g>.



Control System Structure



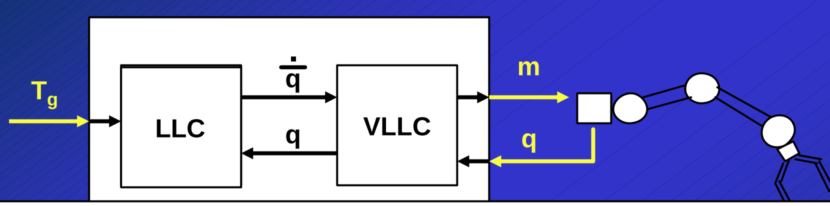
Control System Structure



<u>V</u>ery <u>L</u>ow <u>L</u>evel <u>C</u>ontrol

- Direct HW interaction
  - sensors reading
  - actuator driving
- Joint velocity control loop
- Implementation
  - distributed: one control loop per joint possibly realized by dedicated devices
  - centralized: dynamic compensation, adattative techniques , ...

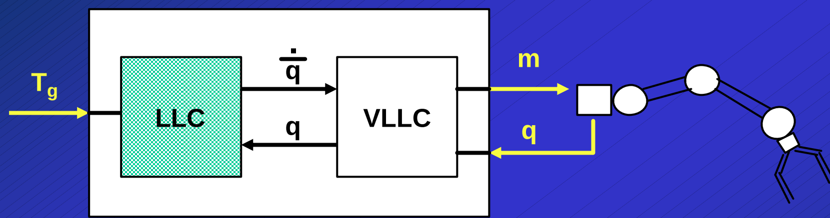
Control System Structure



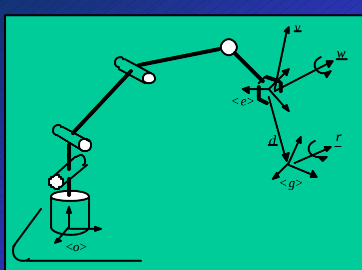
<u>L</u>ow <u>L</u>evel <u>C</u>ontrol

- Cartesian position control loop
- Algorithmic features
  - robust kinematic inversion
  - singularity avoidance
  - obstacle avoidance
  - joint manouvring functionality
  - ...

Control System Structure



Low Level Control



$$e^T \doteq [\, r^T, d^T \,]$$

$$\dot{x}^T \doteq [\, w^T, v^T \,]$$ (abuse of notation)

$$V \doteq \frac{1}{2} e^T e \quad \Rightarrow \quad \dot{V} = - e^T\left(\dot{x} - \dot{x}^*\right)$$

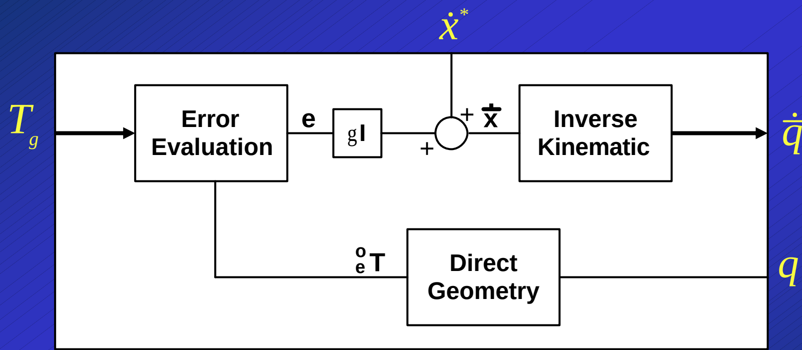
Then, with $\dot{q}$ such that:

$$\dot{x} = \bar{\dot{x}} \doteq g\, e + \dot{x}^* = J\,\dot{q} \quad ; \quad g > 0$$

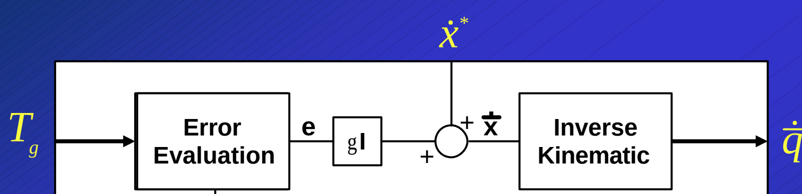
Convergence is guaranteed

(inside the "***dexterous reachable workspace***", provided no singularities occur)

Low Level Control



Low Level Control



Error Evaluation (all vectors projected on <0>)

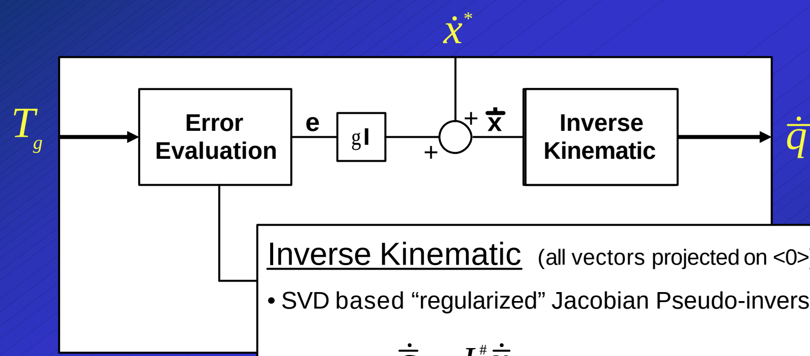
- Linear error by directly evaluating:

$$d = x^* - x$$

- Angular error by Versor Lemma:

$$(i_e \cdot i_g) + (j_e \cdot j_g) + (k_e \cdot k_g) = 1 + 2\cos(J)$$
$$\tfrac{1}{2}\left[(i_e \times i_g) + (j_e \times j_g) + (k_e \times k_g)\right] = r\sin(J)$$

Low Level Control

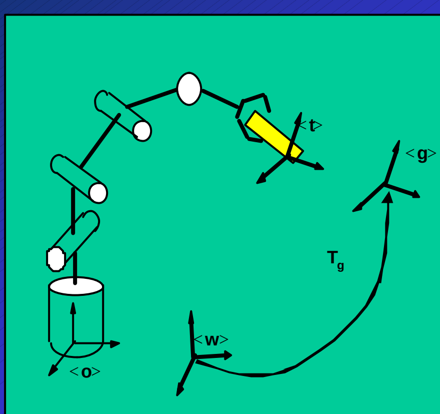


Inverse Kinematic (all vectors projected on <0>)

- SVD based "regularized" Jacobian Pseudo-inversion:

$$\dot{\bar{q}} = J^{\#} \dot{\bar{x}}$$

Low Level Control: Tool and World Frames

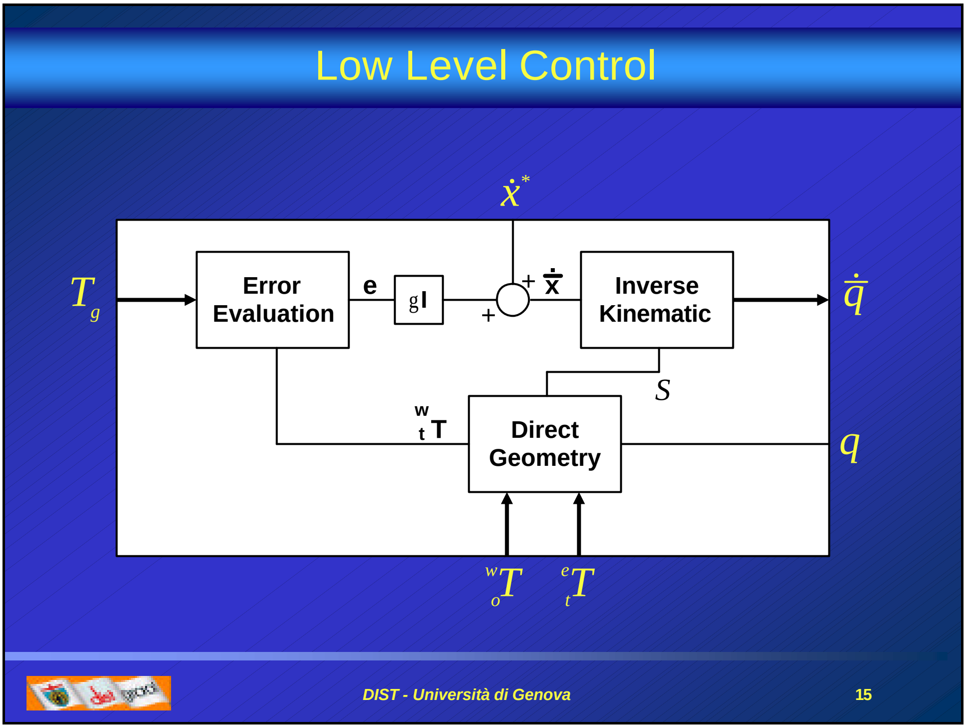


Task objective

To drive the tool frame <t> toward the goal frame <g>.

Remark

The goal transformation matrix <g> is now expressed w.r.t. the world frame <w>.


Low Level Control
$\dot{x}^*$
T_g
Error Evaluation
e
gI
+
+
$\dot{x}$
Inverse Kinematic
$\dot{q}$
S
${}^{w}_{t}T$
Direct Geometry
q
${}^{w}_{o}T$
${}^{e}_{t}T$
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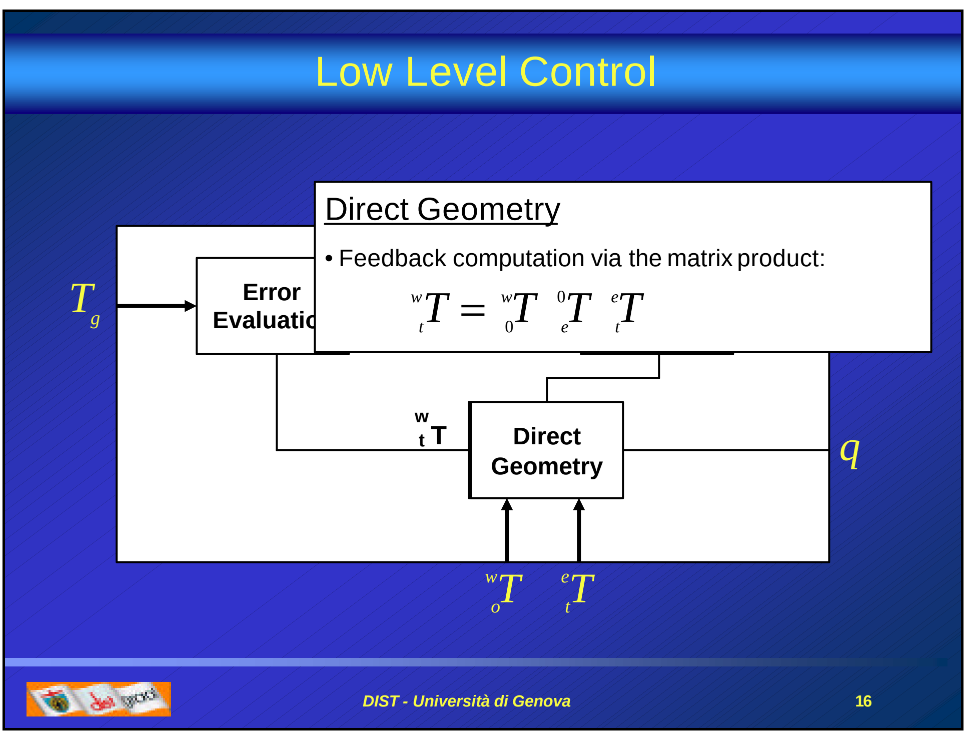
Low Level Control
T_g
Error Evaluatic
Direct Geometry
• Feedback computation via the matrix product:
${}^{w}_{t}T = {}^{w}_{0}T \; {}^{0}_{e}T \; {}^{e}_{t}T$
${}^{w}_{t}T$
Direct Geometry
q
${}^{w}_{o}T$
${}^{e}_{t}T$
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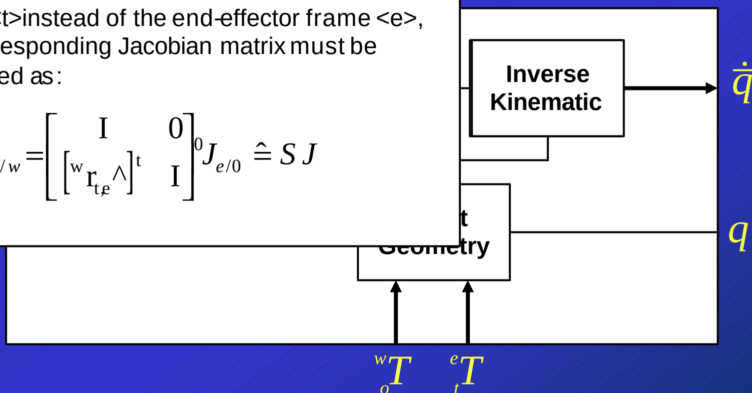
Low Level Control

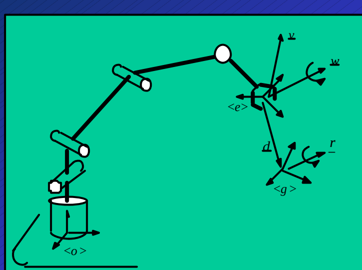
Inverse Kinematic

• Since kinematic must be inverted w.r.t the tool frame <t>instead of the end-effector frame <e>, the corresponding Jacobian matrix must be evaluated as:

$$ {}^{w}J_{t/w} = \begin{bmatrix} I & 0 \\ \left[{}^{w}r_{t,e}\wedge\right]^{t} & I \end{bmatrix} {}^{0}J_{e/0} \triangleq S\,J $$



Non Defective Single Arm: Singularity Avoidance



Manipulability Measure (MM):

$$ m \doteq \det(JJ^{T}) \ge 0 $$

MM Time Derivative:

$$ \dot{m} = p\dot{q} \qquad ; \qquad p \doteq \frac{\partial m}{\partial q} $$

Then, with $\dot{q}$ such that:

$$ \dot{m} = \bar{\dot{m}} \doteq l\,m = p\dot{q} \qquad ; \qquad l > 0 $$

A non decreasing behaviour of *MM* would be guaranteed

Combined Primary and Secondary Task

To combine the two tasks can be introduced a priority that leads to a q̇ such that:

$$\dot{\bar{q}} = J^{\#}\dot{\bar{x}} + h(\dot{\bar{m}} - k\dot{\bar{x}})$$

Goal Frame Reaching (Primary) — Singularity Avoidance (Secondary)

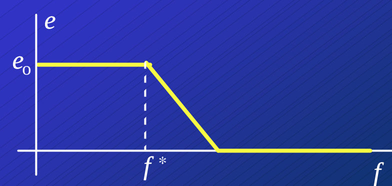
$$k \doteq p J^{\#}$$

$$h \doteq \left[p(I - J^{\#}J)\right]^{\#}$$

Remarks

$$h = (I - J^{\#}J)p^{T}\frac{1}{f+e(f)}$$

$$f = p(I - J^{\#}J)(I - J^{\#}J)p^{T}$$



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$$f = p(I - J^{\#}J)(I - J^{\#}J)p^{T}$$

$$\dot{x} = \dot{\bar{x}}$$

$$\dot{m} = \frac{f}{f+e}\dot{\bar{m}} + \frac{e}{f+e}k\dot{\bar{x}}$$

Combined Primary and Secondary Task

$$\dot{x} = \dot{\bar{x}}$$

$$\dot{m} = \frac{f}{f+e}\dot{\bar{m}} + \frac{e}{f+e} k\,\dot{\bar{x}}$$

Conclusions

-Goal Frame Reaching **and** Singularity Avoidance are guaranteed only for goal frames located inside the "*dexterous reachable workspace*" **and** when the underlying posture is such to have $f \geq f^{*}$ $(e = 0)$

- Singularities **cannot** be avoided in case of goal frames located outside the "*dexterous reachable workspace*"

MM Based Priority Change

To invert the priority of the two tasks can be introduced a Cartesian correction term $\dot{z}$ thus leading to:

$$\dot{\bar{q}} = J^{\#}(\dot{\bar{x}}+\dot{z}) + h[\dot{\bar{m}} - k(\dot{\bar{x}}+\dot{z})]$$

In such a way to fulfill:

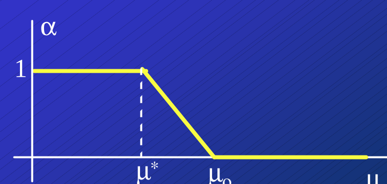
$$\dot{\bar{m}} - k(\dot{\bar{x}} + \dot{z}) = 0 \quad \text{if} \quad m < m_o \quad \text{(and zero otherwise)}$$

In this way:

$$\dot{m} = \dot{\bar{m}} \quad \text{if} \quad m < m_0$$

Then a possible choice for $\dot{z}$ is:

$$\dot{z} = a\, k^{\#}(\dot{\bar{m}} - k\,\dot{\bar{x}})$$



MM Based Priority Change

Remarks

- The proposed control signal with the introduction of the correction term $\dot z$

$$\dot{\bar q} = J^{\#}(\dot{\bar x} + \dot z) + h[\dot{\bar m} - k(\dot{\bar x} + \dot z)]$$

$$\dot z = a\, k^{\#}(\dot{\bar m} - k\,\dot{\bar x})$$

leads to an actual cartesian velocity (when the scalar factor α is unitary)

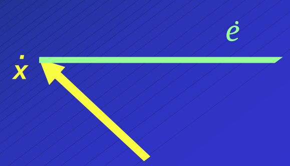
$$\dot x = k^{\#}\dot{\bar m} + [I - k^{\#}k]\dot{\bar x}$$

that induces a cartesian velocity error $\dot e$:

$$\dot e \triangleq \dot{\bar x} - \dot x = k^{\#}k\,\dot{\bar x} - k^{\#}\dot{\bar m}$$

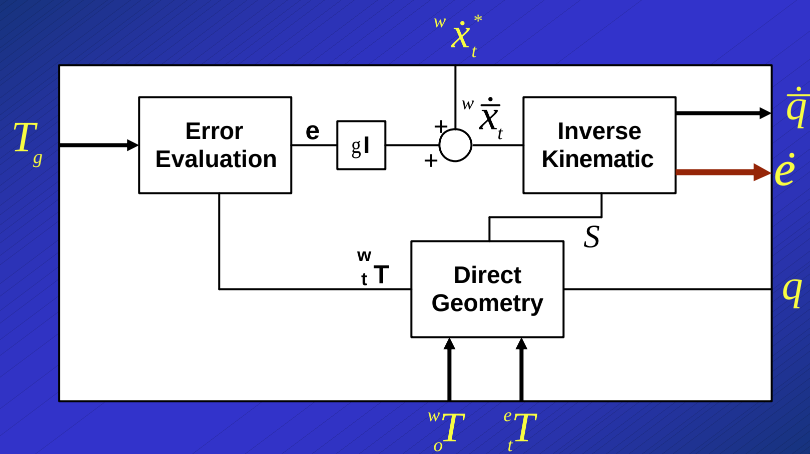
MM Based Priority Change

Remarks

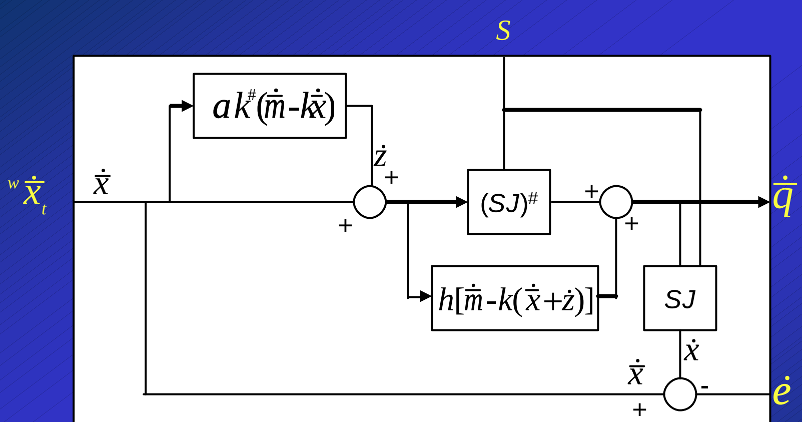


- Goal reaching task **cannot** be achieved in case of goal frames located outside the *"dexterous reachable workspace"*

Implementation: Low Level Control



Implementation: Inverse Kinematic



$$\dot{\bar{q}} = J^{\#}(\dot{\bar{x}} + \dot{z}) + h[\dot{\bar{m}} - k(\dot{\bar{x}} + \dot{z})]$$

$$\dot{e} = a\left(k^{\#}k\,\dot{\bar{x}} - k^{\#}\dot{\bar{m}}\right)$$

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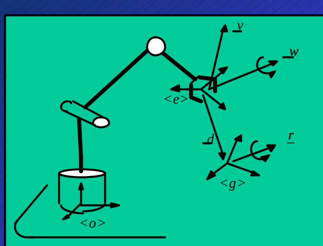
Defective single arm



$$e^T \doteq [\, r^T, d^T \,]$$

$$\dot{x}^T \doteq [\, w^T, v^T \,]$$

$$V \doteq \frac{1}{2} e^T e \quad \Rightarrow \quad \dot{V} = - e^T (\dot{x} - \dot{x}^*)$$

In this case (in general) the equality:

$$\dot{x} = J \dot{q} = \bar{\dot{x}} \doteq g\, e + \dot{x}^* \quad ; \quad g > 0$$

Can be fulfilled in a least square sense only. Therefore the pseudoinversion of the Jacobian matrix thus introduces an error also when the arm is far from its singularities (w.r.t. normal rank) :

$$\dot{e} = [I - JJ^{\#}] \bar{\dot{x}}$$

Defective single arm

A singularity avoidance (w.r.t. normal rank) task can be however introduced again :

$$\dot{m} = \dot{\bar{m}} \doteq l\, m = p\dot{q} \qquad ; \qquad l > 0$$

And also in this case task priority composition can be introduced, leading to:

$$\dot{\bar{q}} = J^{\#}\dot{\bar{x}} + h(\dot{\bar{m}} - k\,\dot{\bar{x}})$$

with:

$$h \doteq \left[p(I - J^{\#}J)\right]^{\#}$$

$$k \doteq p\, J^{\#}$$

If J is normally full rank vector h is a null one

Defective single arm

Task priority inversion can be achieved by again introducing an additional Cartesian term $\dot{z}$ of similar form of full rank case, leading to**:**

$$\dot{\bar{q}} = J^{\#}(\dot{\bar{x}} + \dot{z}) + h[\dot{\bar{m}} - k(\dot{\bar{x}} + \dot{z})]$$

And choose in such a way that:

$$\dot{\bar{m}} - k\,(\dot{\bar{x}} + \dot{z}) = 0 \quad \text{if} \quad m < m_o$$

Then a possible choice for $\dot{z}$ is again:

$$\dot{z} = a\, k^{\#}(\dot{\bar{m}} - k\,\dot{\bar{x}})$$

The correction term $\dot{z}$ induces thus a further error, leading to have:

$$\dot{e} = [I\text{-}JJ^{\#}]\dot{\bar{x}} + a\left[k^{\#}k\,\dot{\bar{x}} - k^{\#}\dot{\bar{m}}\right]$$

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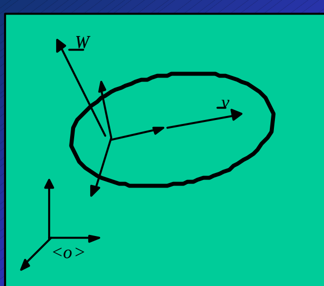
Non-Holonomic Vehicle



For such kind of systems only velocity control is here considered

$$\dot{x} = J\dot{j}$$

where

$$\dot{j}^T \doteq [O^T, n^T]$$

As seen before, the (left) pseudoinversion of the Jacobian matrix introduces a velocity error:

$$\dot{e} = [I - JJ^{\#}]\dot{\bar{x}}$$

In this case, however, it represents the overall error, being a singularity avoidance task a meaningless one.

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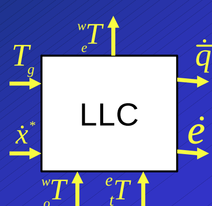
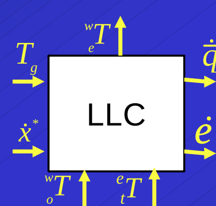
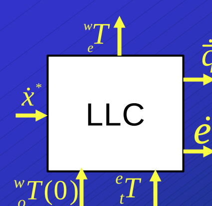
Atomic Modules

- Non-Defective arm
- Defective arm
- Non-holonomic vehicle







Non-Defective arm:

$$\dot{\vec{q}} = J^{\#}(\dot{\vec{x}} + \dot{z}) + h[\vec{m} - k(\dot{\vec{x}} + \dot{z})]$$

$$\dot{e} = a\left(k^{\#}k\,\vec{x} - k^{\#}\vec{m}\right)$$

Defective arm:

$$\dot{\vec{q}} = J^{\#}(\dot{\vec{x}} + \dot{z}) + h[\vec{m} - k(\dot{\vec{x}} + \dot{z})]$$

$$\dot{e} = [I - JJ^{\#}]\dot{\vec{x}} + a\left[k^{\#}k\,\vec{x} - k^{\#}\vec{m}\right]$$

Non-holonomic vehicle:

$$\dot{\vec{q}} = J^{\#}\dot{\vec{x}}$$

$$\dot{e} = [I - JJ^{\#}]\dot{\vec{x}}$$

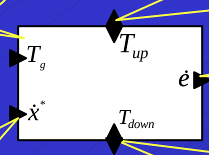
Atomic Modules

In the following the LLC and VLLC modules of each robot will be represented as a unique box (internally realized according to the specific robot features) :

T_g matrix describing the desired position and orientation w.r.t. <w> to be reached by <e> (absent in non-holonomic vehicle)

T_{up} : input/output connection signals with the upper systems

- Input: ${}^{e}_{t}T$
- Output: ${}^{w}_{e}T$



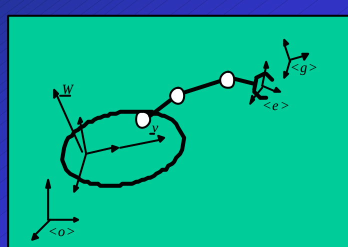
$\dot{e}$ velocity error vector

$\dot{x}^*$ vector describing the desired linear and angular velocities w.r.t. <w> to be assigned to <e>

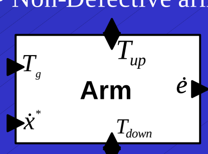
T_{down} : input/output connection signals with the lower systems

- Input: ${}^{w}_{0}T$
- Output: ${}^{0}_{t}T$

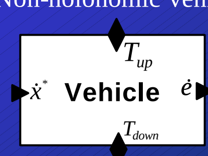
A Preliminary Example



- Non-Defective arm



- Non-holonomic vehicle



Serial Composition

Reference velocity composition

- The vehicle <e> coincides with the arm <0>
- The arm is asked to reach the goal frame
- If it **can** achieve the required <e> velocity

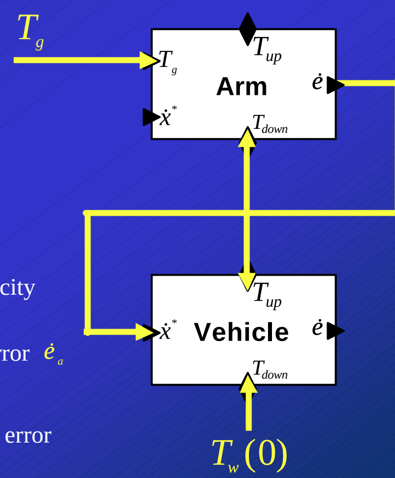
  $\dot{e}_a = 0$

  and no vehicle motion is required
- If the arm **cannot** achieve the the required <e> velocity

  $\dot{e}_a \neq 0$

  then the vehicle is required to compensate for the error $\dot{e}_a$
- The vehicle however **could not** achieve, it also, the required velocity, thus in turn originating its output error

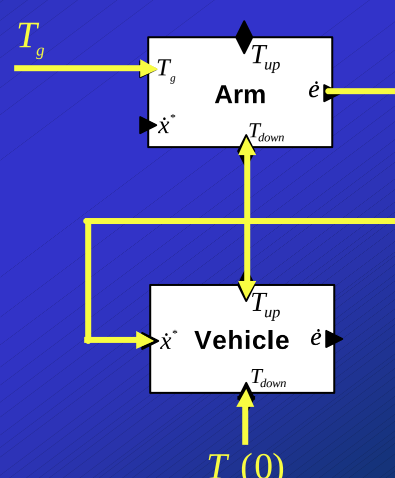
  $\dot{e}_v \neq 0$



Serial Composition

Reference velocity composition

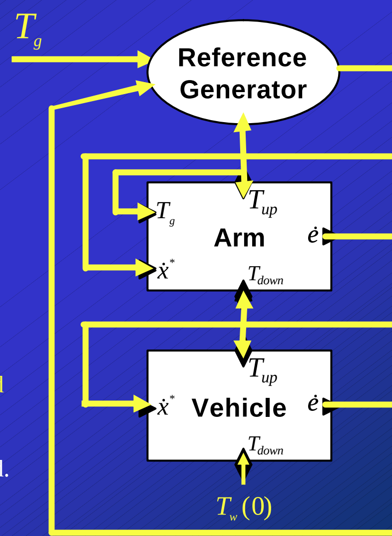
- To compensate also for $\dot{e}_v$ the idea is to send it back again to the arm as an additional Cartesian velocity reference to be assigned before the two systems start moving.
- To this aim some changes must be introduced in the proposed scheme



Serial Composition

Reference velocity composition

- A reference generator block is introduced.
- It first computes the error between the reference frame and the end-effector frame and assigns a reference velocity vector to the arm.
- The arm is therefore controlled via velocity reference only and the position reference T_g is shorted with its the feedback position T_e
- The vehicle error signal $\dot{e}_v$ is sent to the reference generator block within which is added to the previous one.
- The overall procedure can be furtherly reiterated.

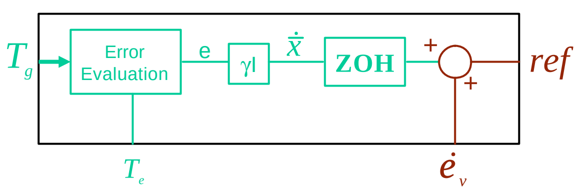


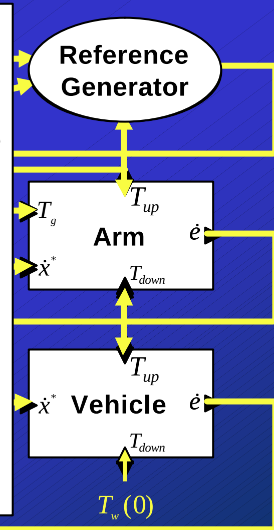
Serial Composition

Reference Generator

This block is divided in two parts, working with different sampling rates:

- The Cartesian error computation (green) is evaluated once and kept constant by the '*zero order hold*' block.
- The error coming from the vehicle (red) is sent to the arm several times within the larger sampling interval





Outline

- Single Arms and Vehicles
  - Non defective single arm
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  - Convergence and stability issues
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  - Object Manipulation
  - Examples

Lyapunov Analysis

$$V \doteq \frac{1}{2}e^T e \quad \Rightarrow \quad \dot V = - e^T\left(\dot x_a + \dot x_v - \dot x^*\right) \qquad \dot{\bar x} \triangleq ge + \dot x^*$$

First iteration: 3 possible cases

1. If the arm can achieve the task by itself:

$$\dot x_a = \dot{\bar x} \qquad \dot x_v = 0 \qquad \Longrightarrow \qquad \dot V = -g e^T e$$

2. The arm introduces an error that the vehicle can compensate for

$$\dot x_a = \dot{\bar x} - \dot e_{a1} \qquad \dot x_v = \dot e_{a1} \qquad \Longrightarrow \qquad \dot V = -g e^T e$$

3. The arm introduces an error that the vehicle cannot compensate for

$$\dot x_a = \dot{\bar x} - \dot e_{a1} \qquad \dot x_v = \dot e_{a1} - \dot e_{v1} \qquad \Longrightarrow \qquad \dot V = -g e^T e + e^T \dot e_{v1}$$

Lyapunov Analysis

$$V \doteq \frac{1}{2} e^T e \quad \Rightarrow \quad \dot{V} = - e^T \left(\dot{x}_a + \dot{x}_v - \dot{x}^* \right) \qquad \dot{\bar{x}} \hat{=} \gamma e + \dot{x}^*$$

Second iteration: 3 possible cases

1. The arm can achieve the new velocity request

$$\dot{x}_a = (\dot{\bar{x}} + \dot{e}_{v1}) - \dot{e}_{a1} \qquad \dot{x}_v = \dot{e}_{a1} - \dot{e}_{v1} \qquad \Longrightarrow \qquad \dot{V} = -\gamma e^T e$$

2. The arm introduces a second error that the vehicle can compensate for

$$\dot{x}_a = (\dot{\bar{x}} + \dot{e}_{v1}) - (\dot{e}_{a1} + \dot{e}_{a2}) \qquad \dot{x}_v = (\dot{e}_{a1} + \dot{e}_{a2}) - \dot{e}_{v1} \qquad \Longrightarrow \qquad \dot{V} = -\gamma e^T e$$

3. The arm introduces a second error that the vehicle cannot compensate for

$$\dot{x}_a = (\dot{\bar{x}} + \dot{e}_{v1}) - (\dot{e}_{a1} + \dot{e}_{a2}) \qquad \dot{x}_v = (\dot{e}_{a1} + \dot{e}_{a2}) - (\dot{e}_{v1} + \dot{e}_{v2}) \qquad \Longrightarrow \qquad \dot{V} = -\gamma e^T e + e^T \dot{e}_{v2}$$

Lyapunov Analysis

Remarks

1. After the i-th iteration the expression of the time derivative of Lyapunov function is

$$\dot{V}_i = -\gamma e^T e + e^T \dot{e}_{vi}$$

2. At first iteration the arm error signal is generated via a projection operation plus a constant term while the vehicle error is the projection operation of the arm error

$$\dot{e}_{a1} = k^{\#} k \, \dot{\bar{x}} - k^{\#} \bar{m} \qquad \dot{e}_{v1} = \left(I - J J^{\#} \right) \dot{e}_{a1}$$

At each step (after the first one) the new terms of both the error signals are generated by the old ones via projection operations:

$$\dot{e}_{ai} = k^{\#} k \dot{e}_{v(i-1)} \qquad \dot{e}_{vi} = \left(I - J J^{\#} \right) \dot{e}_{ai} \qquad \Longrightarrow \qquad \dot{e}_{v(i+1)} = \left[\left(I - J J^{\#} \right) k^{\#} k \right] \dot{e}_{vi}$$

This allows to state that:

$$\dot{V}_i \xrightarrow{i \to \infty} -\gamma e^T e \qquad iff \qquad \dot{e}_{vi} \xrightarrow{i \to \infty} 0$$

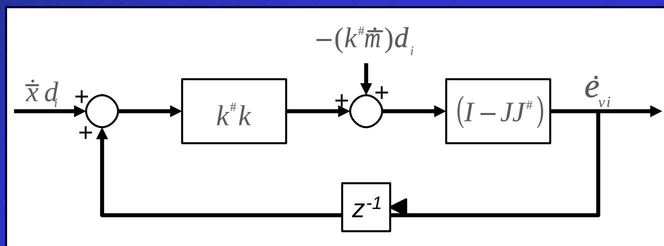
Convergence Issue

$$\dot{e}_{a1} = k^{\#}k\,\dot{\bar{x}} - k^{\#}\dot{\bar{m}}$$

$$\dot{e}_{v1} = (I - JJ^{\#})\dot{e}_{a1}$$

$$\dot{e}_{v(i+1)} = [(I - JJ^{\#})k^{\#}k]\dot{e}_{vi} \qquad i \geq 1$$

Return Error scheme



$$\dot{e}_{vi} \xrightarrow{i\to\infty} 0 \qquad if \qquad Im(k^{\#}k) \cap Im(I - JJ^{\#}) \triangleq \Pi = 0$$

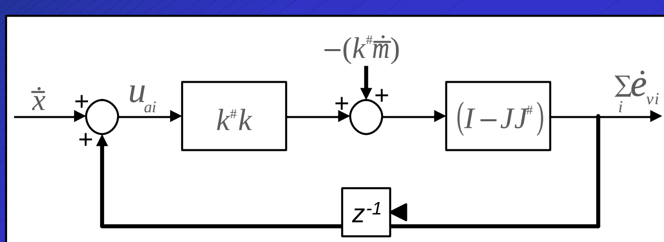
Otherwise

$$\dot{e}_{vi} \xrightarrow{i\to\infty} h \qquad h = Prj_{\Pi}(\dot{\bar{x}} - k^{\#}\dot{\bar{m}}) \neq 0$$

Convergence Issue

Since the sequence of "return input" signals in the overall control system corresponds to $u_{ai} = \dot{\bar{x}} + \sum_i \dot{e}_{vi}$, it then follows it is equivalently generated by the following recursive

Return Input scheme



$$\dot{u}_{ai} \xrightarrow{i\to\infty} \dot{\bar{u}}_a \neq \infty \qquad if \qquad Im(k^{\#}k) \cap Im(I - JJ^{\#}) \triangleq \Pi = 0$$

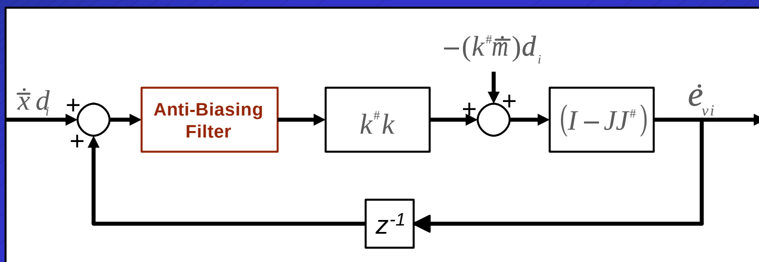
Otherwise

$$\dot{u}_{ai} \sim i\,h \xrightarrow{i\to\infty} \infty \qquad h = Prj_{\Pi}(\dot{\bar{x}} - k^{\#}\dot{\bar{m}}) \qquad \text{Divergence!}$$

Anti-Biasing Filter

To avoid divergence of the u_{ai} signals (or, equivalently, the non convergence to zero of the $\dot{e}_{vi}$ terms) a functional block cutting away the components of the input vectors ($\dot{\bar{x}}$, $-k^{\#}\dot{\bar{m}}$) lying on Π can be inserted

Return Error scheme with Anti-Biasing Filter



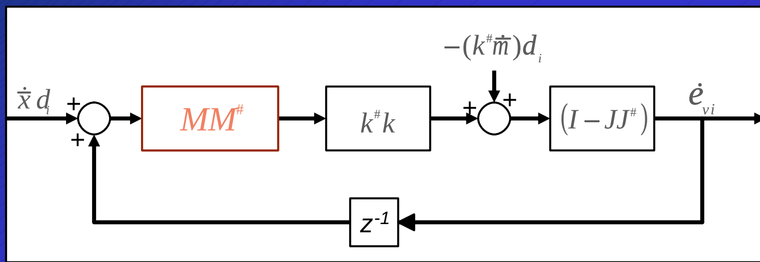
Anti-Biasing Filter

Rationale

- Each input vector can, in general, be decomposed in two parts: one, υ, lying on Π, and one, k, belonging to a subspace Γ orthogonal to υ.
- During the iterations the component k, if not null, reduces in norm and moves within Γ; while the component υ remains unperturbed. Thus implying that every $\dot{e}_{vi}$ contains υ.
- Therefore the difference between two $\dot{e}_{vi}$ ($\hat{=} d\dot{e}_{vi}$) never contains υ, and lyes on Γ.
- By collecting a finite sequence of $d\dot{e}_{vi}$ it is possible to obtain a base matrix M for Γ.
- To cut away the component υ it is then sufficient to project one $\dot{e}_{vi}$ of the return errors on the subspace spanned by M.
- Once υ is filtered away from one return error, the subsequent ones $\dot{e}_{vi}$ will definetely move on Γ, finally converging to zero.

Anti-Biasing Filter

Return Error scheme with Anti-Biasing Filter

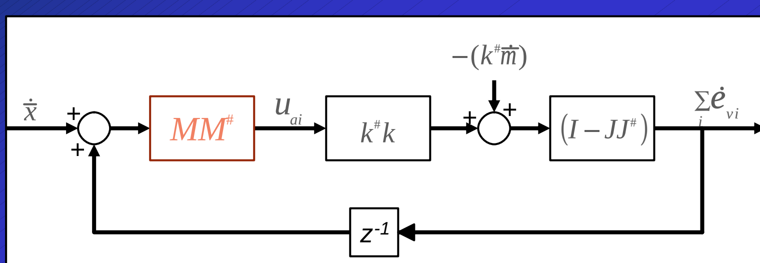


Remarks

- To collect the base matrix M only 6 iterations are required at most.

Anti-Biasing Filter

Return Input scheme with Anti-Biasing Filter



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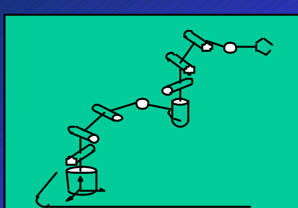
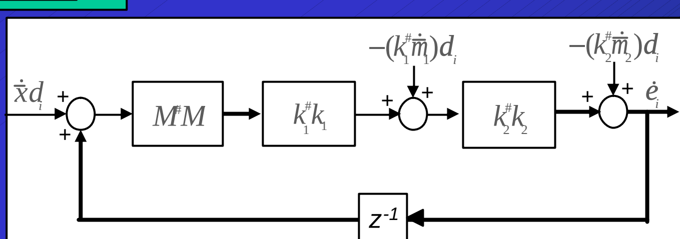
  - Object Manipulation
  - Examples

Examples

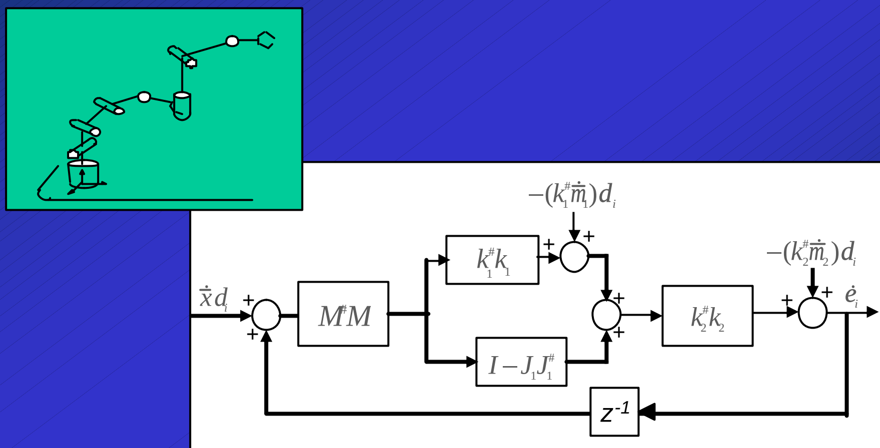
1. Cascade of two non defective arms





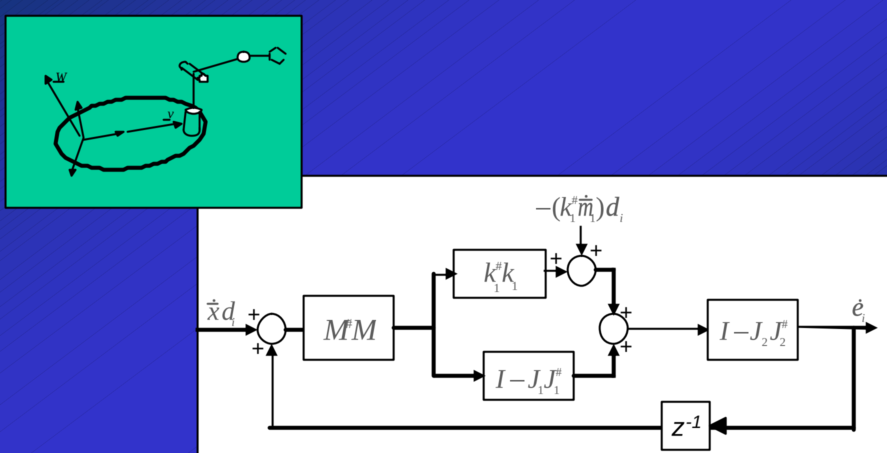
Examples

2. Cascade of a non defective arm and a defective one



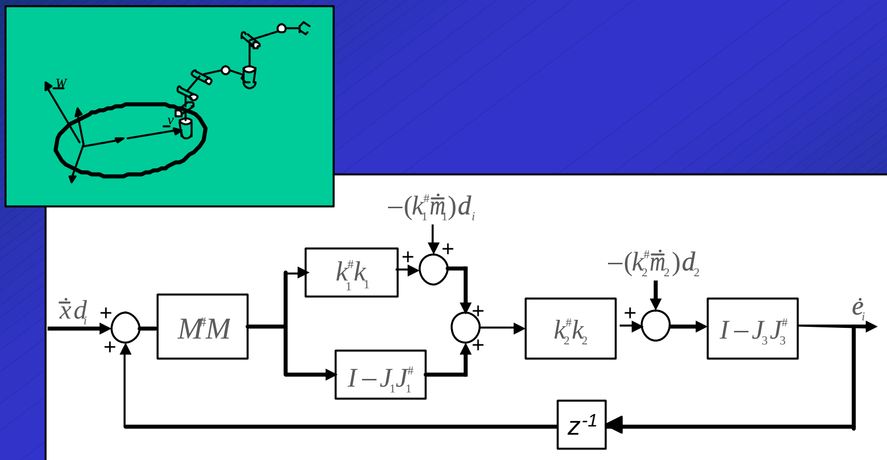
Examples

3. Cascade of a defective arm and a non-holonomic vehicle



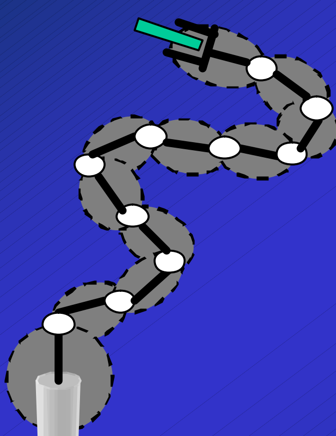
Examples

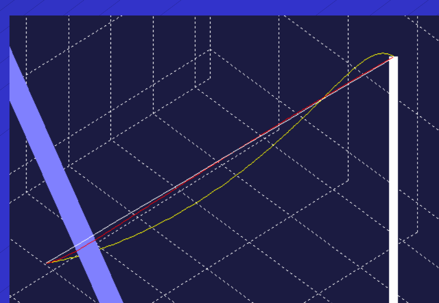
4. Cascade of two arm and a non-holonomic vehicle



Examples

5. Intrinsically modular robot





- 10 Iterations
- 1 Iteration

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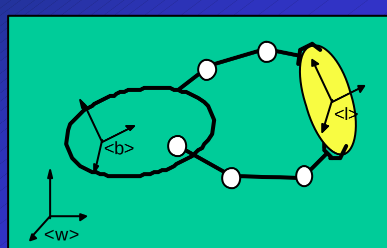
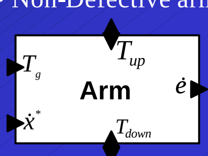
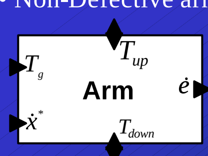
Object Manipulation



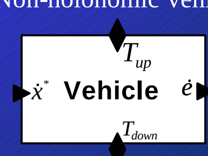
- Non-Defective arm



- Non-Defective arm



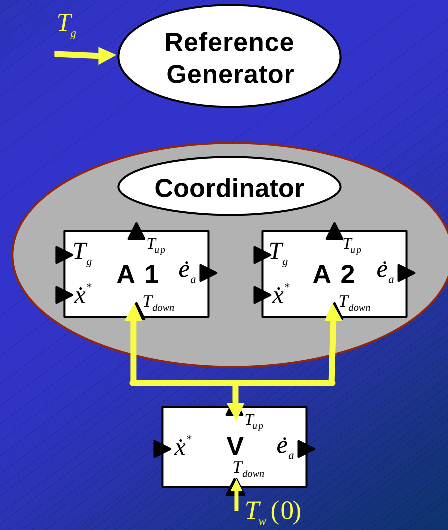
- Non-holonomic vehicle



Object Manipulation

Reference velocity composition

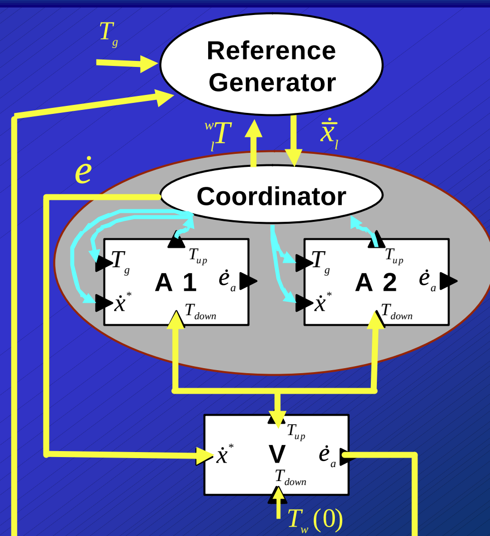
- The vehicle <e> coincides with both arm 1 and arm 2 <0> frames
- The task is expressed in terms of desired position and orientation for the object
- In this case the introduction of a coordinator is necessary to avoid object damaging
- The net effect of the coordinator is that of clustering the two arms, thus allowing to consider them as a single basic robotic unit supporting the object.



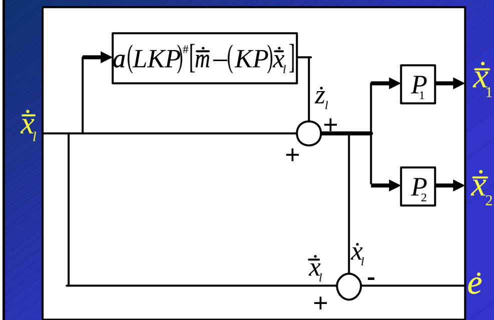
Object Manipulation

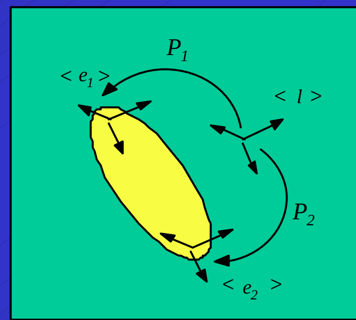
Reference velocity composition

- The coordinator receives, from the reference generator, a reference velocity vector for the object frame and translates it into end-effector reference velocities (and possibly positions) for both the arms.
- It monitors the *MM* of both the arms and, when necessary, computes an additional reference velocity vector for the object guaranteeing to preserve *MM* to both the arms, while maintaining the coordinated motion.
- This additional term is then assigned (via rigid body transformation) to the arms, and the vehicle is asked to compensate for its effect on the object motion.



The Coordinator





$$K \triangleq diag(k_1, k_2) \qquad a \triangleq diag(a_1, a_2)$$

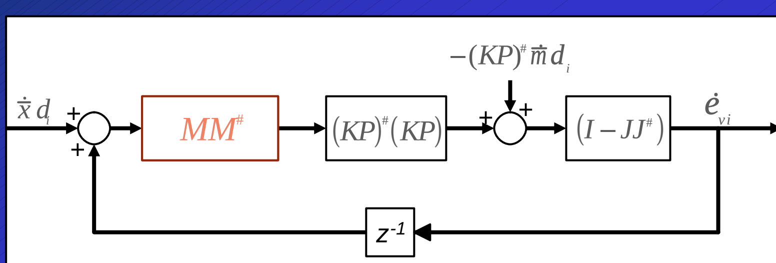
$$P \triangleq (P_1^T, P_2^T)^T$$

$$L \triangleq diag(d_1, d_2) \qquad d_i = \begin{cases} 0 & \text{if } m_i > m_0 \\ 1 & \text{if } m_i < m_0 \end{cases}$$

$$\dot{\vec{m}} \triangleq (\dot{\vec{m}}_1, \dot{\vec{m}}_2)^T$$

The Coordinator

Return Error scheme with Anti-Biasing Filter



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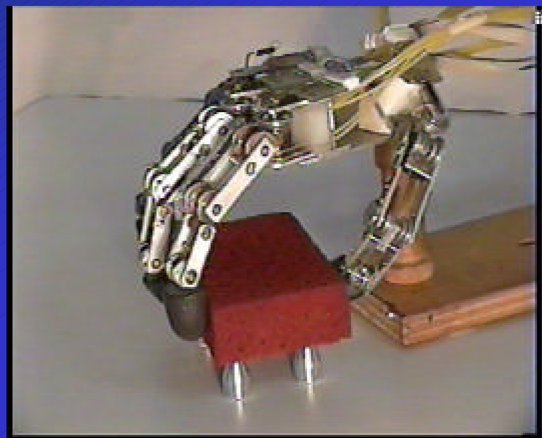
Examples

1. Two non defective arm manipulating an object

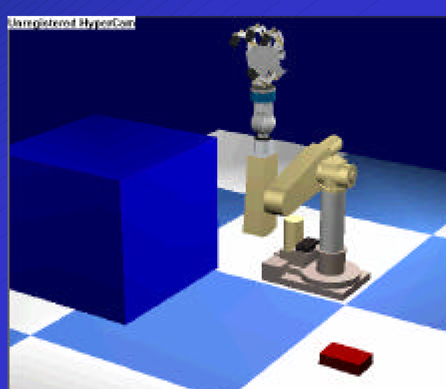
Examples

2. An antropomorphous arm manipulating an object

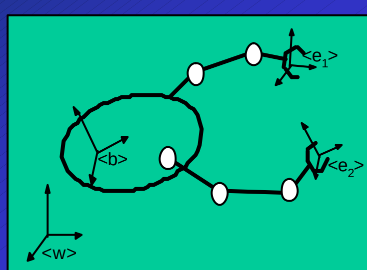


Examples

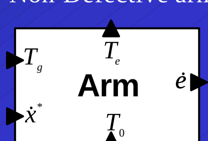
3. A coordinated hand-arm manipulation



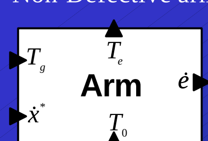
A preliminary example



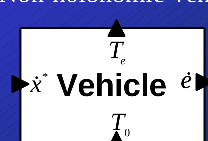
- Non-Defective arm



- Non-Defective arm



- Non-holonomic vehicle



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