On the Design of the Exoskeleton Arm with Decoupled Dynamics

V. Arakelian [1, 2] , Y. Aoustin[1] and C. Chevallereau[1]

[1]IRCCyN, 1 rue de la Noë, BP 92101, F-44321 Nantes Cedex 03, France
[2]Department of Mechanical and Control Systems Engineering
I.N.S.A. Rennes, 20 avenue des Buttes de Coësmes, CS 14315
F-35043 Rennes, France

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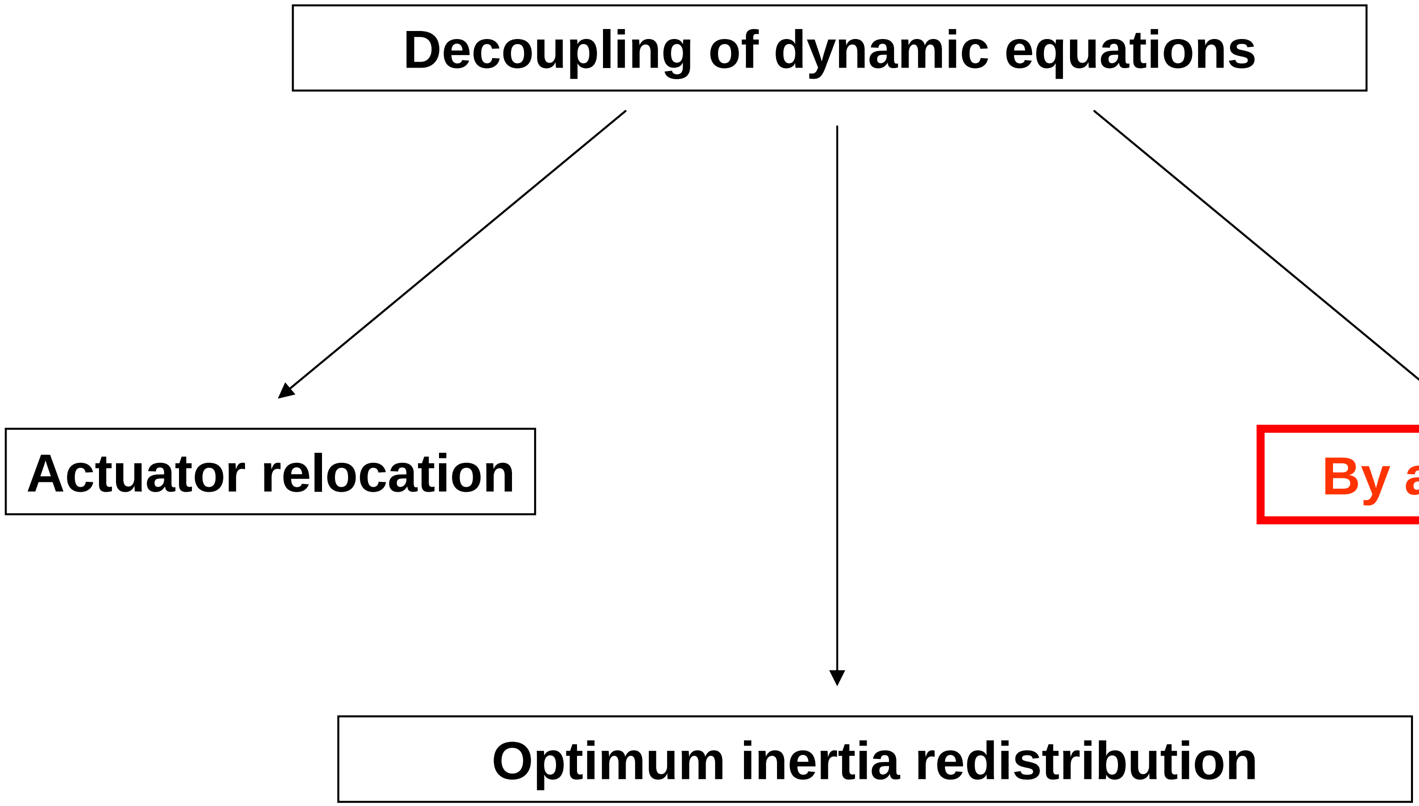


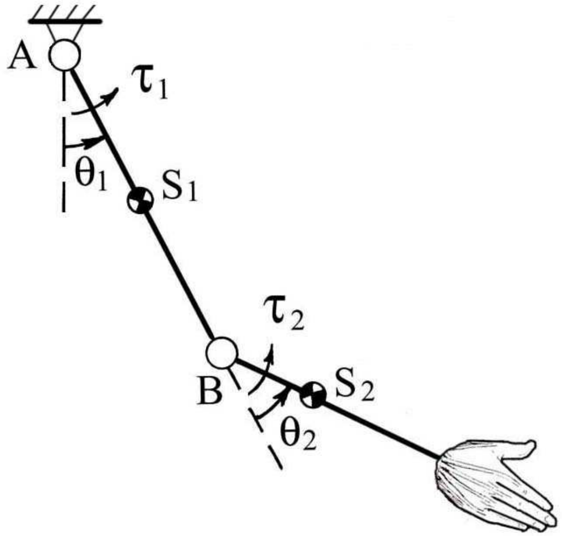


Figure 1

Coupled dynamic equations:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}=\begin{bmatrix}D_{11} & D_{12}\\ D_{21} & D_{22}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix}+\begin{bmatrix}D_{111} & D_{122}\\ D_{211} & D_{222}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1^2\\ \dot{\theta}_2^2\end{bmatrix}+$$

$$\begin{bmatrix}D_{112} & D_{121}\\ D_{212} & D_{221}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\dot{\theta}_2\\ \dot{\theta}_1\dot{\theta}_2\end{bmatrix}+\begin{bmatrix}D_1\\ D_2\end{bmatrix}$$

with $D_{11}=m_1 l_{AS1}^2+m_2 l_1^2+m_2 l_{BS2}^2+2m_2 l_1 l_{BS2}\cos\theta_2+I_{S1}+I_{S2}$; $D_{12}=D_{21}=m_2 l_{BS2}^2+m_2 l_1 l_{BS2}\cos\theta_2+I_{S2}$; $D_{22}=m_2 l_{BS2}^2+I_{S2}$; $D_{111}=0$; $D_{122}=-m_2 l_1 l_{BS2}\sin\theta_2$; $D_{211}=m_2 l_1 l_{BS2}\sin\theta_2$; $D_{222}=0$; $D_{112}=D_{121}=-m_2 l_1 l_{BS2}\sin\theta_2$; $D_{212}=D_{221}=0$; $D_1=(m_1 l_{AS1}+m_2 l_1)g\cos\theta_1+m_2 g l_{BS2}\cos(\theta_1+\theta_2)$; $D_2=m_2 g l_{BS2}\cos(\theta_1+\theta_2)$.

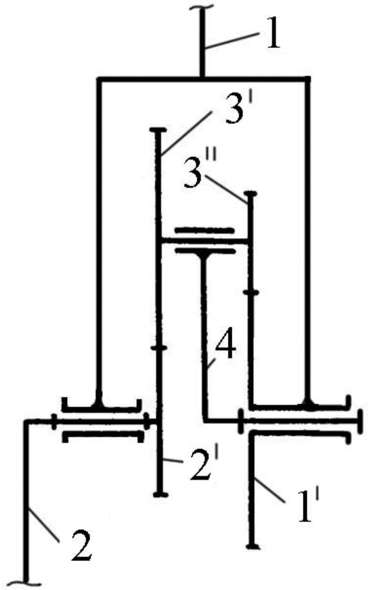


Figure 2. The epicyclic gear train added between links 1 and 2.

The Lagrangian of the manipulator with the added links:

$$L = K - P = \sum_{i=1}^{4} K_i - \sum_{i=1}^{4} P_i =$$

$$0.5\left(m_1 V_{S1}^2 + m_2 V_{S2}^2 + m_3 V_{S3}^2 + m_4 V_{S4}^2\right) +$$

$$0.5\left[I_{S1}\dot{\theta}_1^2 + I_{S2}\left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 + I_{S3}(\dot{\theta}_2 + \dot{\theta}_3)^2 + \right.$$

$$\left. + I_{S4}(\dot{\theta}_2 + \dot{\theta}_4)^2 \right] - \sum_{i=1}^{4} P_i$$

$$\sum_{i=1}^{4} P_i = 0 \Longrightarrow L = 0.5\left[\left(m_1 l_{AS1}^2 + I_{S1} + m l_1^2\right)\dot{\theta}_1^2 + I_{S2}\left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 + I_{S3}(\dot{\theta}_1 + \dot{\theta}_3)^2 + I_{S4}(\dot{\theta}_1 + \dot{\theta}_4)^2\right]$$

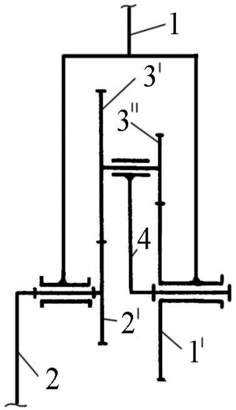


Figure 2. The epicyclic gear train added between links 1 and 2.

The transmission ratio in the epicyclic gear train:

$$\frac{\dot{\theta}_2}{\dot{\theta}_4} = 1 - \frac{Z_{3'} Z_{1'}}{Z_{2'} Z_{3''}}$$

$$Z_{3'} = 2Z_{2'}$$

$$Z_{1'} = Z_{3''}$$

⇒

$$\dot{\theta}_2 = -\dot{\theta}_4$$

$$\dot{\theta}_3 = 2\dot{\theta}_4 = -2\dot{\theta}_2$$

The Lagrangian of the manipulator with the added links can be rewritten as:

$$L = 0.5\left(k_1\dot{\theta}_1^2 + k_2\dot{\theta}_2^2 + k_3\dot{\theta}_1\dot{\theta}_2\right)$$

where

$$k_1 = m_1 l_{AS1}^2 + m l_1^2 + I_{S1} + I_{S2} + I_{S3} + I_{S4}$$

$$k_2 = I_{S2} + 4I_{S3} + I_{S4}$$

$$k_3 = 2\left(I_{S2} - 2I_{S3} - I_{S4}\right)$$

$$\text{if } k_3 = 0\text{, i.e. } I_{S2} = 2I_{S3} + I_{S4}\text{,}$$

⇓

$$L = 0.5\left(k_1\dot{\theta}_1^2 + k_2\dot{\theta}_2^2\right)$$

⇓

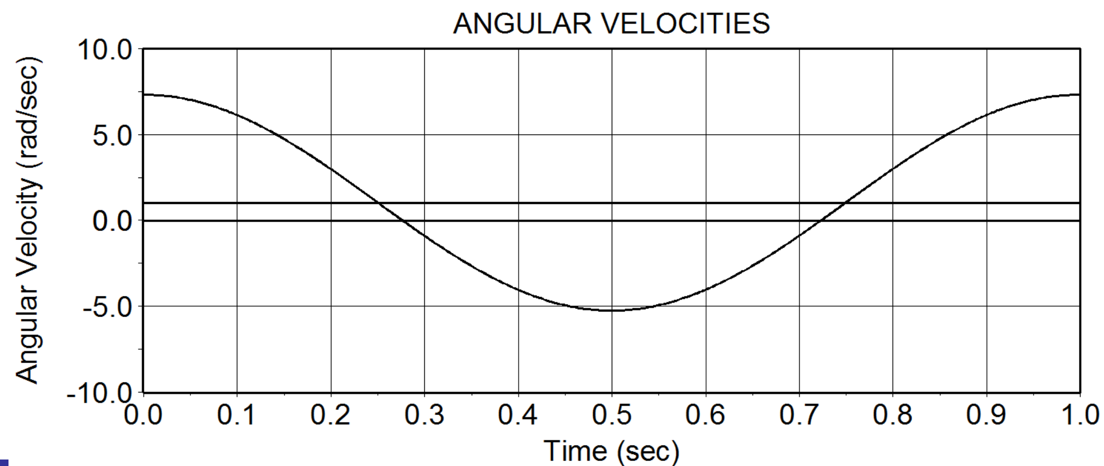
$$\left.\begin{aligned} \tau_1 &= k_1\ddot{\theta}_1 \\ \tau_2 &= k_2\ddot{\theta}_2 \end{aligned}\right\} \quad \text{Dynamic decoupling}$$

- Numerical simulations

The exoskeleton arm parameters with decoupled dynamic equations are the following: $m_1 = 2kg$, $m_2 = 8kg$, $I_{S1} = I_{S2} = 0.1kgm^2$, $l_{AS1} = 0.1m$, $l_{BS2} = 0$ (taking into account that the epicyclic gear train is mainly a balanced system), $I_{S3} = 0.03kgm^2$, $I_{S4} = 0.04kgm^2$ (i.e. $I_{S2} = 2I_{S3} + I_{S4}$).

To better show the dynamic decoupling of motion equations the following input laws have been chosen: $\theta_1 = 60t$ and $\theta_2 = \sin(2\pi t)$ with $0 \le t \le 1s$.

Thus, the angular accelerations are $\ddot{\theta}_1 = 0$ and $\ddot{\theta}_2 = -4\pi^2 \sin(2\pi t)$.



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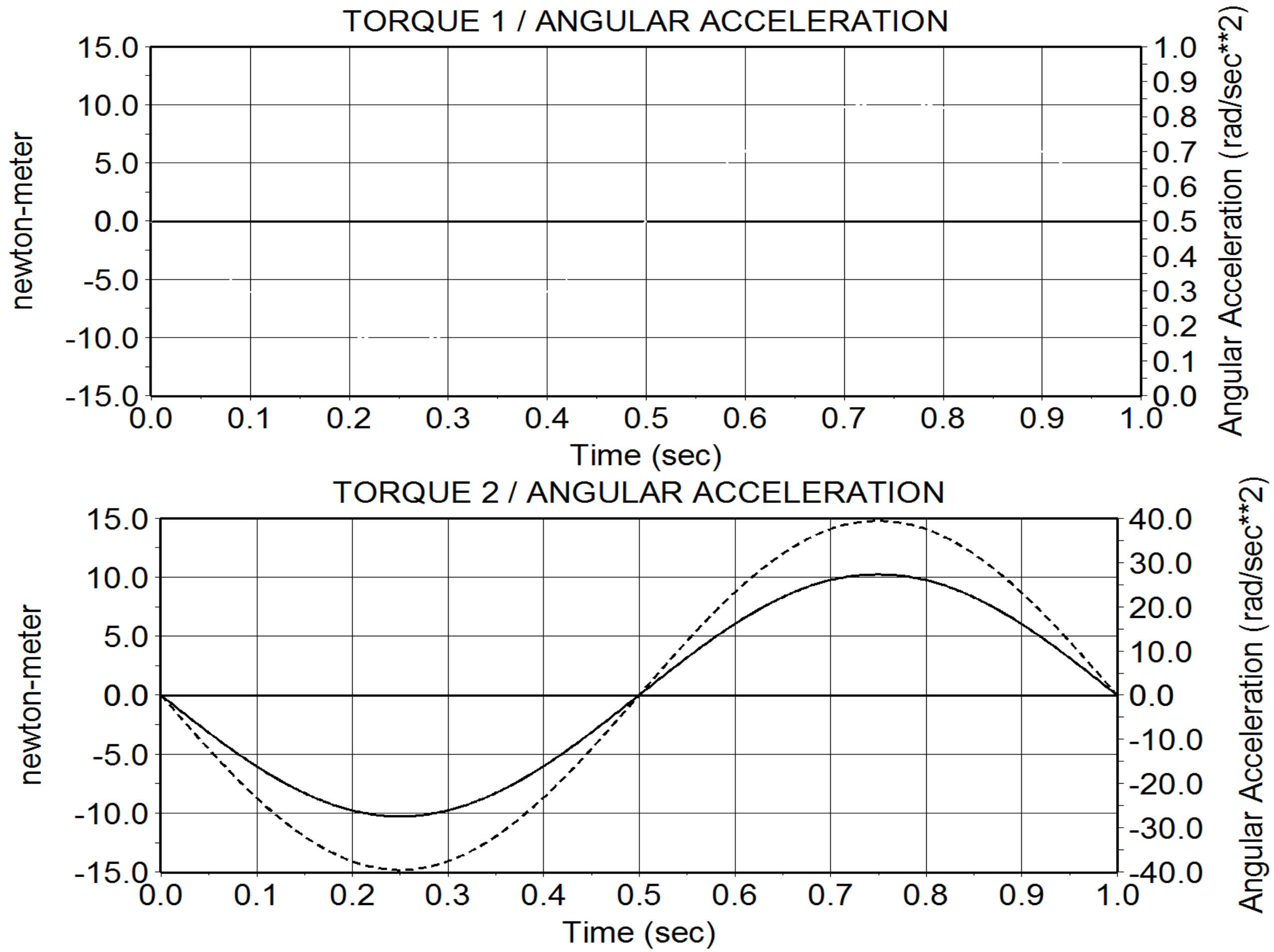

THANK YOU FOR YOUR ATTENTION

Prof. Yannick AOUSTIN

Institut de Recherche en Communications et Cybernétique de Nantes (IRCCyN)

E-mail:

vigen.arakelyan@irccyn.ec-nantes.fr