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Development of an Energy-Saving Manipulator Using Storage Elements and Reaction Wheels

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Abstract

The energy problem, e.g., global warming, exhausted fossil fuel resources, environmental pollution, has captured the attention of people worldwide in recent years. In the manufacturing industry, a lot of machines and robots are consuming a great amount of energy accelerating and braking continuously. Therefore, saving the energy of such mechanical systems as much as possible is a very important task.

In the previous study [1, 2], we examined a method for reducing energy consumption of controlled multibody systems by utilizing storage elements such as springs. Figure 1 shows a model of serial horizontal manipulator equipped with springs. The equations of motion of the system can be expressed as follows

$$\boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}}+\boldsymbol{h}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})=-\boldsymbol{K}(\boldsymbol{\theta}-\boldsymbol{\theta}_n)+\boldsymbol{u}, \tag{1}$$

where $\boldsymbol{\theta}=[\theta_1,\theta_2,\cdots,\theta_N]\in R^N$ is the joint variable vector, $\boldsymbol{M}\in R^{N\times N}$ is the inertia matrix, $\boldsymbol{h}\in R^N$ is the vector of centrifugal and Coriolis forces, $\boldsymbol{u}\in R^N$ is the vector of direct driving torques, $\boldsymbol{K}=\mathrm{diag}[k_1,k_2,\cdots,k_N]\in R^{N\times N}$ is the stiffness matrix, $\boldsymbol{\theta}_n\in R^N$ is the vector of spring mounting positions. We proposed an optimal design method of $\boldsymbol{K}$, $\boldsymbol{\theta}_n$ and $\boldsymbol{u}$ that minimizes the consumed energy based on the optimal control theory. This is the method that uses the natural frequencies and natural modes of the system, and its effectiveness was verified through numerical simulations.

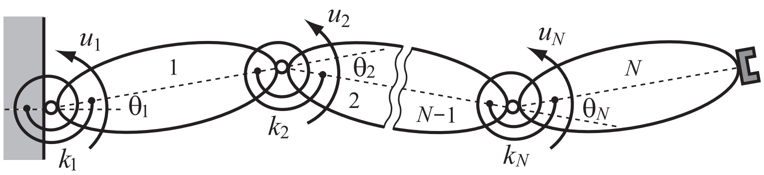

Figure 1: Planar serial manipulator with storage springs.

This paper discusses the actual design and control problems of SCARA robots to realize the concept of proposed energy saving manipulator, and describes some experiments to validate its practical usefulness. Since the proposed method utilizes the free vibration of the system, all joints must be able to rotate freely. Therefore we can not install motors at the joints, instead, we introduce controlled reaction wheels at an arbitrary point on the link and add driving torques from them, as shown in Fig. 2. And, since rotational

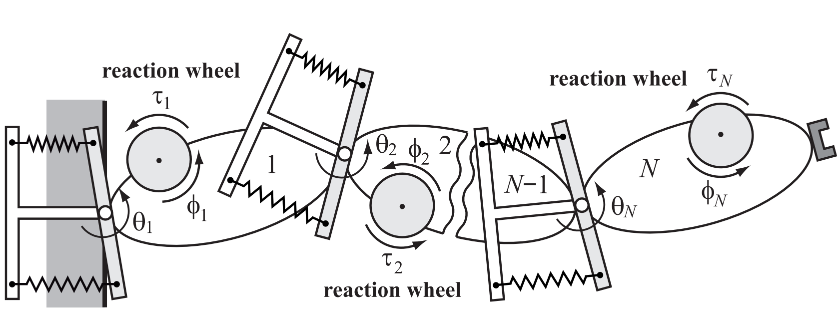

Figure 2: Structure of the proposed energy-saving SCARA manipulator.

springs are more difficult to adjust stiffness and mounting positions, we impose in our experimental setup rotational stiffness between neighboring links by using two linear springs and special spring holders.
The equations of motion of the links and the reaction wheels can be derived as follows

$$\boldsymbol{M}_{\theta\theta}\ddot{\boldsymbol{\theta}} + \boldsymbol{M}_{\phi\theta}^T\ddot{\boldsymbol{\phi}} + \boldsymbol{h} = -\boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{\theta}_n), \tag{2}$$

$$\boldsymbol{M}_{\phi\theta}\ddot{\boldsymbol{\theta}} + \boldsymbol{M}_{\phi\phi}\ddot{\boldsymbol{\phi}} = \boldsymbol{R}\boldsymbol{\tau}, \tag{3}$$

where $\boldsymbol{\theta} = [\theta_1, \theta_2, \cdots, \theta_N]^T$ is the vector of joint variables, $\boldsymbol{\phi} = [\phi_1, \phi_2, \cdots, \phi_N]^T$ is the vector of rotation angles of reaction wheels, $\boldsymbol{M}_{\theta\theta}$, $\boldsymbol{M}_{\phi\theta}$, $\boldsymbol{M}_{\phi\phi}$ are the inertia matrix, $\boldsymbol{h}$ is the vector of centrifugal and Coriolis forces, $\boldsymbol{\tau} = [\tau_1, \tau_2, \cdots, \tau_N]^T$ is the vector of geared driving torques of reaction wheels with gear ratios $\boldsymbol{R} = \mathrm{diag}[r_1, r_2, \cdots, r_N]$, $\boldsymbol{K} = \mathrm{diag}[k_1, k_2, \cdots, k_N]$ is the stiffness matrix, $\boldsymbol{\theta}_n$ is the vector of spring mounting positions. By eliminating $\boldsymbol{\phi}$ from Eqs (2) and (3), and defining $\boldsymbol{M} \equiv \boldsymbol{M}_{\theta\theta} - \boldsymbol{M}_{\phi\theta}^T\boldsymbol{M}_{\phi\phi}^{-1}\boldsymbol{M}_{\phi\theta}$ and $\boldsymbol{u} \equiv -\boldsymbol{M}_{\phi\theta}^T\boldsymbol{M}_{\phi\phi}^{-1}\boldsymbol{R}\boldsymbol{\tau}$, we can obtain the same equations of motion as (1). Hence, for the novel manipulator system shown in Fig. 2, the proposed energy-saving control method is applicable.
To compensate model uncertainties and disturbances, following feedback controller is introduced

$$\boldsymbol{\tau} = -\boldsymbol{R}^{-1}\boldsymbol{M}_{\phi\phi}\boldsymbol{M}_{\phi\theta}^{-T}\boldsymbol{M}\{\ddot{\boldsymbol{\theta}}_d - \boldsymbol{\alpha}(\dot{\boldsymbol{\theta}} - \dot{\boldsymbol{\theta}}_d) - \boldsymbol{\beta}(\boldsymbol{\theta} - \boldsymbol{\theta}_d)\} + \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{\theta}_n), \tag{4}$$

where $\boldsymbol{\theta}_d(t)$ is the desired optimal trajectory, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are matrices that guarantee asymptotic stability.
Figure 3 shows a picture of the 1-DOF energy-saving manipulator prototype. Figure 4 shows the experimental results of trajectory tracking control. As we can see, the tracking error is small enough. We also confirmed that the required torque to achieve the desired task becomes about 10 times smaller than conventional manipulators. This proves that energy consumption can be reduced significantly.

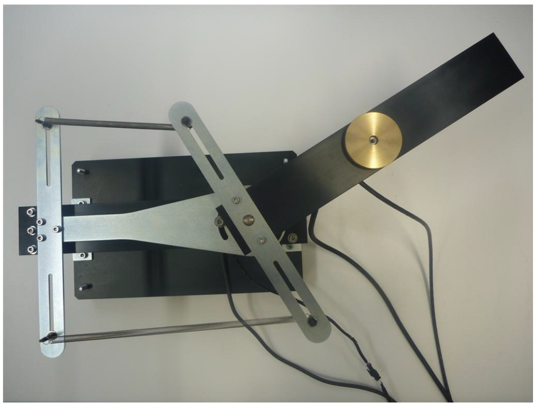

Figure 3: 1-DOF energy saving manipulator.

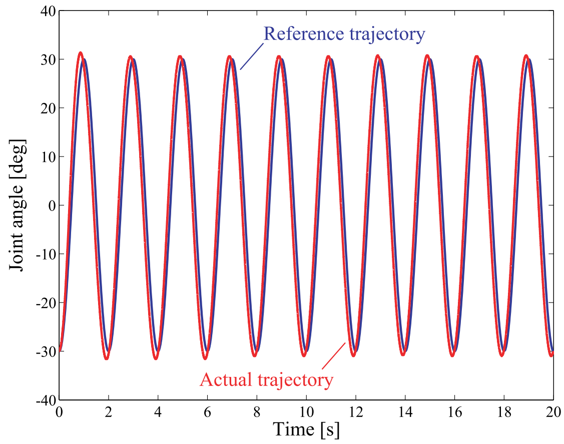

Figure 4: Trajectory tracking control (experiment).

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References

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