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Analysis of the dynamic characteristics of the arm robot

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Abstract
Recent advances in both anthropomorphic robots and bimanual industrial manipulators led to an increased interest in the specific problems of dual-arm manipulation. In the future, we foresee robots performing human-like tasks in domestic and industrial settings. It is, therefore, natural to study specifics of dual-arm manipulation in humans and methods for using the resulting knowledge in robot control. The related scientific problems range from low-level control to high-level task planning and execution. A dual-arm robot, with bi-manual manipulation, can operate in an agile human-like manner. However, because of nonlinear, imprecise modeling and interactive properties, the control of dual-arm robots becomes sophisticated with some limitations. In this study, an analysis of the dynamics model of a dual-arm robot with suitable characteristics in the control design is performed.

Keywords: Dual-Arm Robots, Robotics, Dynamics Model, Variable Structure Control

1. Introduction

Automation systems with applied robotics have already been established in industrial applications for many years [1-9]. Compared to the single-arm robot system, the dual-arm robot can perform human-like dexterity and cooperation. Dual-arm cooperative operation has attracted more and more attention in industrial applications, such as in the assembly of complex parts, manufacturing tasks and handling objects [10-15]. A unified dynamic control method, divided into three modes, namely, independent mode, dependent mode, and half dependent mode, is proposed for a redundant dual-arm robot focusing on the movement and force of the desired task being operated. Attention is devoted to developing a unified formulation of the above three modes. In robotic manipulation systems, a dual-arm configuration is needed for complex operations, like unscrewing a container. It can be helpful for load sharing and manipulation of heavy and bulky objects. The potential of dual-arm manipulation has recently been identified for industrial production setups [16-20].

One of the earliest attempts at dual-arm manipulator control can be found in [21-22], where the author successfully defines task-oriented single-arm and task-oriented dual-arm manipulability to optimize redundant arm joint configurations. In [23-25] proposes the input-output linearization for maintaining contacts between the object and end-effectors. Dividing the assembling task of the two-arm robot into approach and assembly phases, Dauchez *et al.* [26-28] suggest a position control with altered reference position and a hybrid force/position control for manipulating a rigid object. Inspired by the robust nature of variable structure control (VSC), the employ of VSC control is endowed with an adaptive mechanism for robust position and force tracking of the dual arm manipulator [29]. The drawback of this study is that the chattering problem raised by VSC is totally ignored. Similarly, VCS-based position and force controllers are developed in [30-35]. However, the requirement of fully measured outputs, including the contact force, can be very costly.

With the control rules that have been used for the above dual-arm robot, the kinematic model is used with uncertain parameters. That should show the need for a study on building dynamic models with parameters considering the influence of noise in a general form. The content is made to fulfill the stated dynamic modeling objectives.

2. Dual-arm robot dynamics model

A dynamic model of a robot with a fixed base is considered a basis for controller development. A dual-arm robot gives the considered model to handle an object is illustrated in Fig 1.

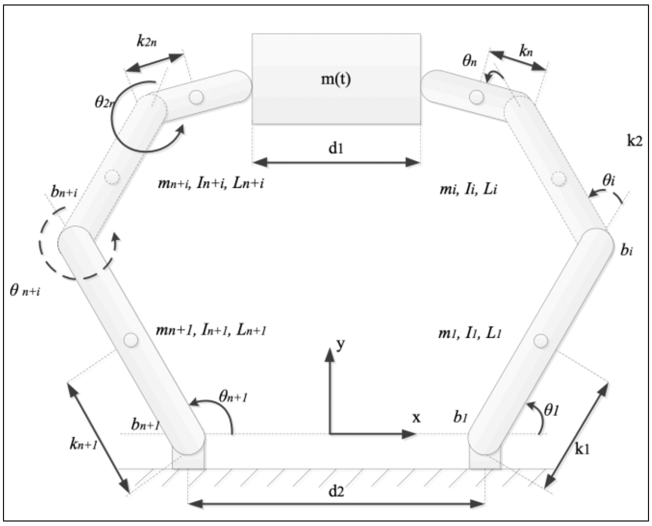

Fig 1: Physical model of the arm robot

The dual arm robot consists of two 2DoF planar robot arms with revolute joints. In this physical model of the system, $m_i, I_i,$ and $L_i (i = 1, 2, 3, 4)$ presents the mass, mass moment of inertia and length of the corresponding links, respectively. In addition, k_i is the distance of the center of mass of each link to the preceding joint and θ_i is the joint angle of the related links. Moreover, $m(t)$ is the mass of the load, d_1 and d_2 denote the width of the rectangle load and the distance between the bases of the two robot arms. In this model, we also consider the viscous in the joints of both robot arms and denoted by b_i. The robot operates in the xy-plane and gravity acts in the negative z-direction.

Because the dual-arm robot handles an object, it is vital to consider the interaction between the robot arms and the object. The robot arms apply forces F_1, F_2 from the arm tips to the load at position (x_1, y_1) and (x_2, y_2), respectively. The object's center is at (x_m, y_m) and it is rotated about φ_5 around z-axis. The friction forces F_{s1xy}, F_{s2xy} are between the arm tips and the load surface in xy-plane. The friction forces F_{s1z}, F_{s2z} are between the arm ends and the object surface along z axis. Because the system is considered in the xy-plane, it can be supposed that

$$F_{s1z} = F_{s2z} = \frac{m(t)g}{2} \tag{1}$$

Using robot forward kinematics for two robot arms, the positions of arm tips can be calculated as follows

$$x_1 = \frac{d_2}{2} + L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \tag{2}$$

$$y_1 = L_1 sin\theta_1 + L_2 sin(\theta_1 + \theta_2) \tag{3}$$

$$x_2 = -\frac{d_2}{2} + L_1 \cos\theta_3 + L_2 \cos(\theta_3 + \theta_4) \tag{4}$$

$$y_1 = L_1 \sin\theta_3 + L_2 \sin(\theta_3 + \theta_4) \tag{5}$$

Then the relation between object's position and robot tips are

$$\begin{aligned} x_m &= \frac{d_2}{2} + L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) - \frac{d_1}{2} cos\varphi_5 \\ &= -\frac{d_2}{2} + L_3 \cos\theta_3 + L_4 \cos(\theta_3 + \theta_4) + \frac{d_1}{2} cos\varphi_5 \end{aligned} \tag{6}$$

$$\begin{aligned} y_m &= L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) - \frac{d_1}{2} \sin\varphi_5 \\ &= L_3 \sin\theta_3 + L_4 \sin(\theta_3 + \theta_4) + \frac{d_1}{2} \sin\varphi_5 \end{aligned} \tag{7}$$

The interaction forces between the dual-arm robot and the object in the xy-plane are $F_1, F_2, F_{s1xy}, F_{s2xy}$. Therefore, the dynamic equations of the object are:

$$m\ddot{x}_m = -F_1 \cos\varphi_5 + F_2 \cos\varphi_5 - F_{s1xy} \sin\varphi_5 - F_{s2xy} sin\varphi_5 \tag{8}$$

$$m\ddot{y}_m = -F_1 \sin\varphi_5 + F_2 \sin\varphi_5 + F_{s1xy} \cos\varphi_5 + F_{s2xy} \cos\varphi_5 \tag{9}$$

$$J\ddot{\varphi}_5 = (F_{s1xy} - F_{s2xy})\frac{d_1}{2} \tag{10}$$

From (8) and (9) it can be shown that

$$m(\ddot{x}_m \sin\varphi_5 - \ddot{y}_m \cos\varphi_5) = -\sin^2\varphi_5 (F_{s1xy} + F_{s2xy}) - \cos^2\varphi_5 (F_{s1xy} + F_{s2xy}) \tag{11}$$

or

$$F_{s1xy} + F_{s2xy} = m(\ddot{x}_m \sin\varphi_5 - \ddot{y}_m \cos\varphi_5) \tag{12}$$

Combine with (10), friction forces F_{s1xy} and F_{s2xy} can be calculated as follows:

$$F_{s1xy} = [m(\ddot{x}_m \sin\varphi_5 - \ddot{y}_m \cos\varphi_5) + \frac{2J\ddot{\varphi}_5}{d_1}] \tag{13}$$

$$F_{s2xy} = [m(\ddot{x}_m \sin\varphi_5 - \ddot{y}_m \cos\varphi_5) - \frac{2J\ddot{\varphi}_5}{d_1}] \tag{14}$$

Substituting (13) and (14) into (8) results in;

$$\Delta F = F_2 - F_1 = m\frac{(1+\sin^2\varphi_5)\ddot{x}_m + \sin\varphi_5 \cos\varphi_5 \ddot{y}_m}{\cos\varphi_5} \tag{15}$$

In order to handle the object effectively, the following conditions must be obtained:

$$F_{s1xy}^2 + F_{s1z}^2 \le (\mu F_1)^2, F_{s2xy}^2 + F_{s2z}^2 \le (\mu F_2)^2 \tag{16}$$

Since the direction of acting forces F_1 and F_2 are always direct towards the object, the friction force equation that provides a positive signed solution for both F_1 and F_2 should be selected.

$$F_1 = \frac{1}{\mu}\sqrt{F_{s1xy}^2 + F_{s1z}^2}, \quad F_2 = F_1 + \Delta F \tag{17}$$

$$F_2 = \frac{1}{\mu}\sqrt{F_{s2xy}^2 + F_{s2z}^2}, \quad F_1 = F_2 - \Delta F \tag{18}$$

The dual arm robot system includes two 2DoF robot arms that handles and the object can be considered as two separated robot arm with external forces F_1, F_{s1xy} for the first arm and F_2, F_{s2xy} for the second arm. Therefore, the governing equations for the dual-arm robot system are as following:

$$M(\bar{\mathbf{q}})\ddot{\bar{\mathbf{q}}} + C(\bar{\mathbf{q}}, \dot{\bar{\mathbf{q}}}) = \bar{\boldsymbol{\tau}} + J(\bar{\mathbf{q}})^T \bar{F} - \boldsymbol{\beta}\dot{\bar{\mathbf{q}}} + \bar{\mathbf{w}} \tag{19}$$

Where $\bar{\mathbf{q}} = [\theta_1, \theta_2, \theta_3, \theta_4]^T$ is angular vector, $\bar{\boldsymbol{\tau}} = [\tau_1, \tau_2, \tau_3, \tau_4]^T$ is torque input vector, $\bar{\mathbf{F}} = [F_{1x}, F_{1y}, F_{2x}, F_{2y}]^T$ is external force vector, $\bar{\omega} = [\omega_1, \omega_2, \omega_3, \omega_4]^T$ is external disturbance torque vector.

The external force component can be calculated from F_1, F_{s1xy}, F_2, and F_{s2xy} as following:

$$F_{1x} = F_1 \cos\varphi_5 + F_{s1xy} \sin\varphi_5, \quad F_{1y} = F \sin\varphi_5 - F_{s1xy} \cos\varphi_5 \tag{20}$$

$$F_{2x} = -F_2 \cos\varphi_5 + F_{s2xy} \sin\varphi_5, \quad F_{2y} = -F_2 \sin\varphi_5 - F_{s2xy} \cos\varphi_5 \tag{21}$$

In addition, $\mathbf{M}(\bar{\mathbf{q}})$ is inertia matrix, $\mathbf{C}(\bar{\mathbf{q}}, \dot{\bar{\mathbf{q}}})$ is Coriolis matrix, $\mathbf{J}(\bar{\mathbf{q}})$ is Jacobian matrix, β is viscous friction matrix, and they are calculated as following:

$$\mathbf{M}(\bar{\mathbf{q}}) = \begin{bmatrix} A_1 + A_2 + 2A_3\cos\theta_2 & A_2 + A_3\cos\theta_2 & 0 & 0 \\ A_2 + A_3\cos\theta_2 & A_2 & 0 & 0 \\ 0 & 0 & A_4 + A_5 + 2A_6\cos\theta_4 & A_5 + A_6\cos\theta_4 \\ 0 & 0 & A_5 + A_6\cos\theta_4 & A_5 \end{bmatrix};$$

$$\mathbf{C}(\bar{\mathbf{q}}, \dot{\bar{\mathbf{q}}}) = \begin{bmatrix} -A_3 \sin\theta_2 (\dot{\theta}_2^2 + 2\dot{\theta}_1\dot{\theta}_2) \\ -A_3\dot{\theta}_1\dot{\theta}_2 \sin\theta_2 \\ -A_6 \sin\theta_4 (\dot{\theta}_4^2 + 2\dot{\theta}_3\dot{\theta}_4) \\ -A_6\dot{\theta}_3\dot{\theta}_4 \sin\theta_4 \end{bmatrix};$$

$$\boldsymbol{\beta} = \begin{bmatrix} b_1 & 0 & 0 & 0 \\ 0 & b_2 & 0 & 0 \\ 0 & 0 & b_3 & 0 \\ 0 & 0 & 0 & b_4 \end{bmatrix};$$

$$\mathbf{J}(\bar{\mathbf{q}}) = \begin{bmatrix} -L_1\sin\theta_1 - L_2\sin(\theta_1+\theta_2) & -L_2\sin(\theta_1+\theta_2) & 0 & 0 \\ L_1\cos\theta_1 + L_2\cos(\theta_1+\theta_2) & L_2\cos(\theta_1+\theta_2) & 0 & 0 \\ 0 & 0 & -L_3\sin\theta_3 - L_4\sin(\theta_3+\theta_4) & -L_4\sin(\theta_3+\theta_4) \\ 0 & 0 & L_3\cos\theta_3 + L_4\cos(\theta_3+\theta_4) & L_4\cos(\theta_3+\theta_4) \end{bmatrix};$$

3. Conclusions

The Dynamics formulation of the dual arm robot is addressed in the paper. Dissimilar to other works, the robot considered in the paper can relocate and rotate the object simultaneously toward the goal of archiving fast dynamical transient response and system robustness. On the basis of the built dynamics model, the control design with variable structure control has become extremely clear. The future work of the research on robotic systems in general, and in dual-arm manipulation in particular, will be integrating elements from systems theory with tools from cognitive methodologies. These will involve the consideration of vision and learning capabilities in the actual feedback design. This seems necessary in advanced collaborative control tasks where the manipulators have incomplete knowledge of the environment and might have been assigned their tasks independently.

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