Journal of the Industrial Technology Research Institute.
Korea Maritime University. Vol. 12. 1994.

물체 이동을 위한 협조 팔 시스템의 비결합에 관한연구

최형식*

A Decoupling Analysis of Object Transport of Two-Arm System

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Abstract

This paper presents a new control scheme for decoupling the dynamics of two coordinating robot manipulators. A simple full-state feedback scheme with configuration dependent gains can be devised to decouple the system dynamics such that the dynamics of each arm and that of an object held by the two arms is independent of one another. As an example, the proposed control scheme is applied to coordinate the motion of a candidate two-arm system; a parallel-connected system composed of two motor systems whose shafts are coupled together by a spring-and-damper coupling. The advantage of the proposed scheme is that the same control scheme can be applied for both the closed kinematic chain(object-grasping) case and open kinematic chain(no object-grasping) case.

1. INTRODUCTION

Many tasks arise in assembly, repair and inspection that require multiple robot manipulators to perform in a coordinated manner. A multitude of challenging research issues arise from multi-arm coodinated control[1-5]. One of the fundamental problems that control designers face is the fact that

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a dual-arm robotic system manipulating a common load is described by a closed kinematic chain, resulting in system dynamic constraints and a reduction in the degrees of freedom [6]. In [7], Ahmad and Luo described a technique for coordinated motion control of multi-arm manipulators for welding applications. There, a redundant manipulater with seven degree-of-freedom is required to weld on specific trajectory along a table. Constraints on singular conditions and motion limits are incorporated into a performance measure to be optimized. The approach requires off-line path planning and, in effect, uses a master/slave control scheme. Carignan and Akin [8] transformed the dual-arm problem to a hierarchial control structure whereby a complete minimization is performed on a reduced-order model of the system in order to construct the payload trajectory; then a parameter minimization is done to find the force distribution of the arms on the payload. This approach yields a suboptimal solution but incorporates the dynamics and control issues into nonconflicting performance measures.

Seraji [9] develops an adaptive position/force control appoach to the dual-arm problem. By employing an adaptive PID struture, knowledge of the mathematical model of the system is not required. The coupling effects between the manipulators, through the common payload, and modelled as distubances in the position and force equations which are then compensated for in the adaptation rule. In [11] , Ro and Youcef-Toumi present a leader-follower control approach, but with a reference model structure. The leader manipulator is directed according to a presribed reference model system while the follower arm follows via interacting force feedback. Robustness issues of the control scheme in the presence of actuator nonlinearities and model uncertainties as well as bounded disturbances are presented in [12].

In this paper, an issue of dynamic decoupling robot arms manipulating a common object is addressed. The object is assumed to be rigid and rigidly held by the two robot arms. Depending on the arm configuration and the speed with which the object is manipulated, the dynamic coupling between two robot arms and that of the object can be negligibly small and consititute a significant portion of the overall dynamics, In this paper, a new control scheme is introduced which incorporates a decoupling condition into the two-arm coordination problem. Stability of the approach in a linear sense is guaranteed, while the robustness of the approach can be obtained in a manner similar to what is shown in [12].

2. TWO-ARM DYNAMICS

The equations of motion for two robot arms grasping an object can be expressed as the following:

$$H_1\,\ddot{q}_1 + C_1(q_1,\ \dot{q}_1) = T_1 + J_1^{\ T}F_1 \tag{1a}$$

$$H_2\,\ddot{q}_2 + C_2(q_2,\ \dot{q}_2) = T_2 + J_2^{\ T}F_2 \tag{1b}$$

$$M_0\,\ddot{x}_0 + C_0(x_0,\ \dot{x}_0) = -\ L_1^{\ T}F_1 -\ L_2^{\ T}F_2 \tag{1c}$$

where q_1 and q_2 are $n\times 1$ joint angle vectors for arms 1 and 2; x_0 is the $n\times 1$ vector representing the position and orientation of the object center in the inertial space; T_1 and T_2 are the $n\times 1$ joint torque vectors for arms 1 and 2; H_1 and H_2 are the mass matrices of size $n\times n$ associated with arms 1 and 2; M_0 is the mass matrix associated with the object; C_1 and C_2 are nonlinear force vectors of size $n\times 1$, respectively; and J_1 and J_2 are the $n\times n$ Jacobian matrices of arms 1 and 2. Forces $F_1(F_2)$ represent $n\times 1$ vectors of forces and moments at the interaction between the center of the object and the interaction between arm 1 (arm 2) and the object, and $n\times n$ matrices L_1 and L_2 repersent transformations associated with finite lengths between the center of the object and the interaction points. Similar expressions for the dynamics of two-arm systems have been used by [8], [15], and others Above expression can be rewritten in a matrix form as

$$M(x)\ \ddot{x} = u - C(x,\ \dot{x}) + G(x)F \tag{2}$$

where

$$x = \begin{bmatrix} q_1 \\ q_2 \\ x_0 \end{bmatrix},\quad u = \begin{bmatrix} T_1 \\ T_2 \\ 0 \end{bmatrix},\quad C = \begin{bmatrix} C_1 \\ C_2 \\ C_0 \end{bmatrix},\quad F = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}$$

$$M = \begin{bmatrix} H_1 & 0 & 0 \\ 0 & H_2 & 0 \\ 0 & 0 & M_0 \end{bmatrix},\quad G = \begin{bmatrix} J_1^{\ T} & 0 \\ 0 & J_2^{\ T} \\ -\ L_1^{\ T} & -\ L_2^{\ T} \end{bmatrix}$$

where u is control input vector. Eq.(2) states that there are $5n$ unknowns, x and F, with $3n$ equations. However, $2n\times 1$ vector F can be expressed as functions of other $3n$ unknowns using the kinematic constraints imposed on the system due to rigid grasping, as shown in [8]. The kinematic constraints due to the closed-kinematic chain formed by grasping can be expressed by $2n$

algebraic equations

$$x_0 = r_1(q_1) = r_2(q_2) \tag{3}$$

where r_1 and r_2 represent the object position and orientation in arm 1 and 2 cooordinates, respectively. Equation (3) can be rewritten as

$$\alpha(x) \equiv \begin{bmatrix} r(q_1) - x_0 \\ r(q_2) - x_0 \end{bmatrix} = 0 \tag{4}$$

where α represents the closed kinematic chain, and is always equal to $2n \times 1$ null vector for all the time. The force F can be expressed as a function of known variables. To do this, first taking the second derivative of constraints (4) with respect to time yields

$$\dot{\alpha}_x \dot{x} + \alpha_x \ddot{x} = 0 \tag{5}$$

and substituting eq. (2) to the resulting expression (5) and solving for F as

$$\dot{\alpha}_x \dot{x} + \alpha_x M(x)^{-1}(u - C(x, \dot{x}) + G(x)F) = 0 \tag{6}$$

Hence, expressing eq. (6) with respect to F and substituting eq. (2) yields the resulting expresston of two-arm dynamics as

$$\ddot{x} = P(u - C(x, \dot{x})) - Q\dot{x} \tag{7}$$

where

$$P = M^{-1}[\ I - G\ (\alpha_x M^{-1} G)^{-1} \alpha_x M^{-1}]$$

$$Q = M^{-1} G\ (\alpha_x M^{-1} G)^{-1}\ \dot{\alpha}_x$$

and α_x and $\dot{\alpha}_x$ are $2n \times 3n$ partials of constraint (4) with respect to x and that with respect to time, respectively. The above equations of motion holds whenever $(\alpha_x M^{-1} G)^{-1}$ exists.

3. A DECOUPLING CONTROL SCHEME VIA STATE FEEDBACK

Here, we propose a state feedback control scheme that will try to "decouple" as much as possible the dynamics of each arm from the other as well as from that of the object we need to diagonalize two $3n \times 3n$ matrices, namely, P and Q. For this purpose, we consider

$$u = -K_1(x)\,\dot{x} - K_2(x)x + \hat{C} \tag{8}$$

where K_1 and K_2 are feedback gain matrices and feedforward term, $\hat{C}$ are defined as

$$K_1 = \begin{bmatrix} k_{11}(q_1) & k_{12}(q_2) & k_{13}(x_0) \\ K_{21}(q_1) & k_{22}(q_2) & k_{23}(x_0) \\ 0 & 0 & 0 \end{bmatrix}, \quad k_2 = \begin{bmatrix} g_{11}(q_1) & g_{12}(q_2) & g_{13}(x_0) \\ g_{21}(q_1) & g_{22}(q_2) & g_{23}(x_0) \\ 0 & 0 & 0 \end{bmatrix}, \quad \hat{C} = \begin{bmatrix} \hat{c}_1 \\ \hat{c}_2 \\ 0 \end{bmatrix}$$

The feedforward term represents the estimates of the nonlinear Coriolis, centrifugal, and gravity forces. We note that the bottom row has to be zero because there is no control available for the object. Each element, k_{ij} or g_{ij}, is an $n \times n$ matrix of feedback gains that is dependent on the configuration of the arms. This is because the matrices, P and Q, are control action shown in eq. (8) to the two-arm system of (7), the resulting equations of motion, assuming $C = \hat{C}$ become

$$\ddot{x} + [\ PK_1(x) + Q\ ]\ \dot{x} + PK_2(x)x = 0 \tag{9}$$

Looking at the above expression, the decoupling of the dynamics of each arm can be achieved if we can diagonalize the coefficient matrices associated with the velocity vector and the position vector terms. Of our prime concern is to decouple the dynamics between the two arms. This can be achieved by choosing the off-diagonal gain elements k_{12}, k_{21}, g_{12}, and g_{21} such that the 12-th element and 21-th element of the coefficient matrics become null, that is,

$$(PK_1 + Q)_{12} = (PK_1 + Q)_{21} = 0 \quad \text{and} \quad (PK_2)_{12} = (PK_2)_{21} = 0 \tag{10}$$

For this particular case, the following choice of gain elements will satisfy the condition shown in eq.(8):

$$k_{12} = -\ p_{11}{}^{-1}[\ p_{12}k_{22} + q_{12}]\ ,\ k_{12} = -\ p_{22}{}^{-1}[\ p_{21}k_{11} + q_{21}] \tag{11a}$$

$$g_{12} = -\ p_{11}{}^{-1}p_{12}k_{22},\ \text{and}\ \ g_{21} = -\ p_{22}{}^{-1}p_{21}k_{11} \tag{11b}$$

where p_{ij} and q_{ij} represent the ij-th element of P and Q, respectively. Similarly, the decoupling of the object dynamics from the first arm dynamics can be realized by choosing k_{13}, k_{31}, g_{31}, and g_{31} elements such that

$$(PK_1+Q)_{31} = (PK_2+Q)_{31} = 0 \quad \text{and} \quad (PK_2)_{13} = (PK_{2)})_{31} = 0 \tag{12}$$

The conditions in (8) and (10) can not be simultaneously satisfied because there is no control associated with the object; this is represented by the null row vectors for the last rows of K_1 and K_2. The stability of the overall system as well as the desired performance of esch arm depend on choosing appropriate gains for diagonal elements, k_{ij} and g_{ij}, such that the individual secon order matrix equations have stable coefficients. One complication with the above approach can result because of the fact that these gains are configuration dependent.

The approach shown above is useful in that we can define the desired dynamics of each arm independent of the other and of the object. Also, it is particularly useful because the control scheme can be readily adapted for controlling the arms separately in the case of open kinematic chain (no object-graspong mode). In case the robot arms are maneuvering in space independently, the gains for the off-diagonal elements of K_1 can be set to zero. If at some point an object is detected and the arms start manipulating the object, the gains of off-diagonal elements can be obtained according to (8). This simple but very efficient control feature can be essential in space assembly and repair, or even in factory assembly, where the operating mode of dual-arm may have to change frequently from the "object-grasping" mode to "no object-grasping" mode.

4. A SIMPLE EXAMPLE

The control scheme in (8) is applied to coordinate the motion of two simple mass-spring-damper systems(representing simple motor systems) coupled by massless object whose dynamics is characterized by a spring and a damper(see Fig.1). It is quite obvious to see that the dynamics of this dual-mass system can be described by

$$\begin{aligned} \dot{x}_1 &= A_1 x_1 + B_1 u_1 - h_1 f_c \\ \dot{x}_2 &= A_2 x_2 + B_2 u_2 + h_2 f_c \end{aligned} \tag{13}$$

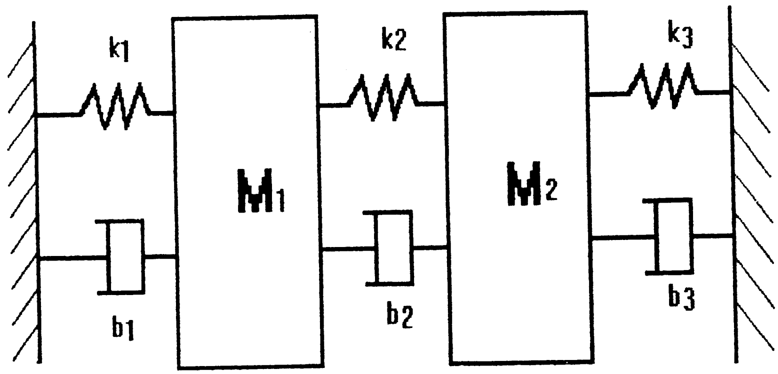

Figure 1. **A one-dimentional coordination**

where $x_i^T = [\ x_i,\ \dot{x}_i]$ and f_c is the coupling force and is defined as $f_c = K_c(x_1 - x_2)$ where the coupling matrix K_c which is diagonal matrix. We can rewrite(11) by incorporating the coupling force relation,

$$\dot{x} = Ax + Bu \tag{14}$$

where

$$A = \begin{bmatrix} A_1 - h_1K_c & h_1K_c \\ h_2K_c & A_2 - h_2K_c \end{bmatrix},\ B = \begin{bmatrix} B_1 & 0 \\ 0 & B_2 \end{bmatrix},\ x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix},\ u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

According to the proposed control scheme, we choose the control

$$u = -[\ g_1\ \ g_2\ \ g_3\ \ g_4]\ x \tag{15}$$

such that the resulting overall equations of motion become

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_1 - h_1K_c - B_1g_1 & h_1K_c - B_1g_2 \\ h_2K_c - B_2g_3 & A_2 - h_2K_c - B_2g_4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{16}$$

Then,the decoupling condition becomes obvious in that the off-diagonal terms have to go to zero, or

$$g_2 = B_1^* h_1K_c \quad \text{and} \quad g_3 = B_2^* h_2K_c \tag{17}$$

where * represents a pseudo-inverse. Finally. the decoupled dynamics of mass system 1(or 2) can be shaped into a desired form by choosing the gains for g_1 (or g_2). The stability of each system can also be guaranteed whenever $(A_i - h_i K_{c,} B_i)$ for i=1,2 is controllable.

5. CONCLUSION

A decouping control scheme for dual-arm coordination is devised. The scheme decouples the dynamics of each arm from the other and that of the object, and utilizes a straight forward full-state feedback with configuration dependent gains. A simple example of a linear one-dimensional coordination is illustrated to demonstrate the usefulness of the control scheme. Based on the closed-loop two-arm system, a syability condition is derived. In the actual implementation, a certain form of realizing the configuration dependent gains have to be further investigated along with the issues of stability and performance robustness.

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