⊙ 研究論文

A Dynamic Decoupling of Two Cooperating Robot System and Stability Analysis

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협조로보트 시스템의 동적 Decoupling과 안정도연구

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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. A condition for stability is shown. The advantage of the proposed scheme is that the same control scheme can be applied both for 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 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]. Also, Ahmad and Luo described a technique for coordinated motion control of multi－arm manipulators for welding applications[7]. 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 mea-

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sure 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, are modelled as distubances in the position and force equations which are then compensated for in the adaptation rule. Ro and Youcef-Toumi[11] 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[12] of the control scheme in the presence of actuator nonlinearities and model uncertainties as well as bounded disturbances are presented.

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 reference[12].

2. Two-arm Dynamics

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

$$H_1\ddot{q}_1+C_1(q_1,\dot{q}_1)=T_1+J_1^TF_1 \quad (1a)$$
$$H_2\ddot{q}_2+C_2(q_2,\dot{q}_2)=T_2+J_2^TF_2 \quad (1b)$$
$$M_0\ddot{x}_0+C_0(x_0,\dot{x}_0)=-L_1^TF_1-L_2^TF_2 \quad (1c)$$

where q_1 and q_2 are $n\times1$ joint angle vectors for arms 1 and 2 ; x_0 is the $n\times1$ vector representing the position and orientation of the object center in the inertial space ; T_1 and T_2 are the $n\times1$ 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 $n\times1$, respectively ; and J_1 and J_2 are the $n\times n$ Jacobian matrices of arms 1 and 2. Forces $F_1(C_2)$ represent $n\times1$ 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 lenghths between the center of the object and the interaction points. Similar expressions for the dynamics of two-arm systems have been used[8,15]. Above expression can be rewritten in a matrix form as

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

where

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

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

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 as

$$x_0=r_1(q_1)=r_2(q_2) \qquad (3)$$

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

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

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

$$\dot{\alpha}_x\dot{x}+\alpha_x\ddot{x}=0 \qquad (5)$$

Substituting Eq. (2) to the resulting expression (5) and solving for F yield

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

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

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

where

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

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

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

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

$$K_1=\begin{bmatrix} k_{11}(q_1) & k_{12}(q_2) & k_{13}(x_0) \\ k_{21}(q_1) & k_{22}(q_2) & k_{23}(x_0) \\ 0 & 0 & 0 \end{bmatrix},$$

$$K_2=\begin{bmatrix} g_{11}(q_1) & g_{12}(q_2) & g_{13}(x_0) \\ g_{21}(q_1) & g_{22}(q_2) & g_{23}(x_0) \\ 0 & 0 & 0 \end{bmatrix}, \hat{C}=\begin{bmatrix} \hat{c}_1 \\ \hat{c}_2 \\ 0 \end{bmatrix}$$

The feedforward term $\hat{C}$ 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. By the control action shown in Eq.(8) to the two-arm system of (7), the resulting equations of motion become

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

where if we can measure C exactly, $C=\hat{C}$ is satisfied. 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. 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,

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

where

$$P=\begin{bmatrix} p_{11}(q_1) & p_{12}(q_2) & p_{13}(x_0) \\ p_{21}(q_1) & p_{22}(q_2) & p_{23}(x_0) \\ p_{31}(q_1) & p_{31}(q_2) & p_{31}(q_2) \end{bmatrix}$$

$$R=\begin{bmatrix} r_{11}(q_1) & r_{12}(q_2) & r_{13}(x_0) \\ r_{21}(q_1) & r_{22}(q_2) & r_{23}(x_0) \\ r_{31}(q_1) & r_{31}(q_2) & r_{31}(q_2) \end{bmatrix}$$

For this particular case, the following choice of gain elements will satisfy the condition shown in Eq.(10) :

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

where p_{ij} and r_{ij} represent the ij-th element of P and R, 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

$$(PK_1+R)_{13}=(PK_2+R)_{31}=0 \text{ and}$$
$$(PK_2)_{13}=(PK_2)_{31}=0 \tag{12}$$

The conditions in (10) and (12) 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 depends on choosing appropriate gains for diagonal elements, k_{ij} and g_{ij}, such that the individual second 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 (10). 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. Stability Condition and Analysis

In this section, general conditions to guarantee the stability of the closed-loop two-arm dynamic system are discussed. By the proposed control action in (11,12), Eq.(9) can be expressed as $3n\times 1$ matrix equation

$$\ddot{x}+K_d\dot{x}+K_px=Q(x,\ \dot{x}) \tag{13}$$

where K_d and K_p are the $3n \times 3n$ diagonal matrices and $Q(x, \dot{x})$ is coupling term. The dynamics of each arm is assumed to be affected by only the coupling forces instead of other forcing terms such as compensation errors or model uncertainties, etc. Under this condition, a stability robustness analysis is shown with the assumption.

Suppose that

(i) the function $Q(x, \dot{x})$ including coupled forces and input disturbances is upper bounded for $T - T_0 < \sigma$ as

$$\| Q(x, \dot{x}) \| \le \lambda_2(\| x \| + \| \dot{x} \|) \quad (14)$$

uniformly in t where an appropriate $\lambda_2 > 0$ is constant.

With assumption (i), $\| x \| \to 0$ and $\| \dot{x} \| \to 0$ for all sufficiently large t.

4.1 Proof of Stability

For the proof of the stability of the two - arm system, Eq.(13) can be expressed as

$$\dot{x} = y,\ \dot{y} = -K_p x - K_d y + Q(x, \dot{x}) \quad (15)$$

Also, a Lyapunov function $V = V(x, y)$ is chosen as in [16]

$$2V = \langle y + K_d x, y + K_d x \rangle + \langle y, y \rangle + 2 \langle K_p x, x \rangle \quad (16)$$

Here the Lyapunov function $V(x, y)$ is a convex function and positive scalar because the matrix K_p is defined as positive definite. In addition to the positive quantity of the Lyapunov, an estimate for $\dot{V} = \frac{d}{dt} V(x(t), y(t))$ corresponding to any solution (x, y) of Eq.(15) is required. For convenience, $Q(x, \dot{x})$ is expressed as Q(.). Differentiating the Lyapunov function of Eq.(16) yields

$$V = \langle y + K_d x, -K_d y - K_p x + Q(.) + K_d y \rangle + \langle y, -K_d y - K_p x + Q(.) \rangle + 2 \langle K_p x, y \rangle$$

$$= \langle K_d x, K_p x \rangle - \langle y, K_d y \rangle + \langle 2y + K_d x, Q(.) \rangle \quad (17)$$

The estimate of the first term in the right hand side of Eq.(17) is

$$\langle K_d x, K_p x \rangle = \langle K_d K_p x, x \rangle \ge \lambda_d \lambda_p \| x \|^2 = \lambda_{dp} \| x \|^2 \quad (18)$$

where λ_d and λ_p are the least eigenvalues of matrix K_d and K_p, respectively. Also, $\lambda_{dp} \equiv \lambda_d \lambda_p > 0$ because K_d and K_p are defined as diagonal positive definite matrices. In a similar way, the second term of Eq.(17) is estimated as

$$\langle y, K_d y \rangle = \langle K_d y, y \rangle \ge \lambda_d \| y \|^2 \quad (19)$$

Applying Schwarz's inequality to estimate the remaining term in the expression $\dot{V}$ in Eq.(17) yields

$$| \langle 2y + K_d x, Q(.) \rangle | \le \lambda_3(\| x \| + \| y \|) \| Q(.) \| \quad (20)$$

for some constant $\lambda_3 > 0$ whose magnitudes can be estimated with (14) as

$$| \langle 2y + K_d x, Q(.) \rangle | \le \lambda_3(\| x \| + \| y \|) \| Q(.) \| \le \lambda_3(\| x \| + \| y \|) \lambda_2 (\| x \| + \| y \|) \le 2\lambda_2 \lambda_3(\| x \|^2 + \| y \|^2) \quad (21)$$

where λ_{md} is the largest eigenvalue of K_d matrix such that $\lambda_3 = \max(2, \lambda_{md})$. Thus, the inequality is achieved by putting all the estimates of the various terms in Eq.(18,19) into the expression for $\dot{V}$ in Eq.(17) as

$$\dot{V} \le -(\lambda_{dp} - 2\lambda_2 \lambda_3) \| x \|^2 - (\lambda_d - 2\lambda_2 \lambda_3) \| y \|^2 \quad (22)$$

Hence, if λ_2 is defined as

$$\lambda_2 \le \Lambda_2 = \frac{1}{2} \min(\lambda_{dp} \lambda_3^{-1}, \lambda_{dp} \lambda_3^{-1}) = \frac{1}{2} \min(\lambda_p, 1)\, \lambda_{dp} \lambda_3^{-1}$$

which is a sufficient condition for $\dot{V}$ to become negative semi-definite. In Eq.(22), with the sufficient condition,

$$\dot{V} \leq -2\lambda_5(\|x\|^2 + \|y\|^2) \tag{23}$$

where $\lambda_5 = \min(\lambda_{dp} - 2\lambda_2\lambda_3,\ \lambda_c - 2\lambda_2\lambda_3)$. Because $\dot{V} \leq 0$, the above inequality implies that $\|x\| \to 0$ and $\|y\| \to 0$ as $t \to \infty$

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. Based on the closed-loop two-arm system, a stability condition is derived and the stability is studied. In the actual implementation, a some form of realizing the configuration dependent gains have to be further investigated along with the issues of stability and performance robustness.

References

1) E. Nakano. S. Ozaki, T. Ishida and I. Kata, "Cooperational Control of the Anthropomorphous Manipulator MELANM", Proc. of Fouth Int'l Conf. on Architectural Robots, 1974, pp. 251 260.
2) S. Fujii and S. Kurono, "Coordinated Computer Control of a Pair of Manipulators, "Proc. of Fourth World Congress on Theory of Machines and Mechanisms, 1975, pp. 411 - 417.
3) J. Y. S. Luh and Y. F. Zheng, "Computation of Input Generalized Forces for Robots with Closed Kinematic Chain Mechanisms." IEEE Journal of Robotics and Automation, Vol. RA 1, No.2, pp. 95 - 103
4) S. Hayati, "Hybrid Position Force Control of Mult-arm Cooperating Robots," Proc. of IEEE Int'l Conf. on Robotics and Automation, 1986, pp. 82 - 89.
5) T. J. Tarn. A. K. Bejczy, and X. Yun, "Coordinated Control of Two robot Arms," Proc, of IEEE Int'l Conf. on Robotics and Automation, 1989, pp. 1193 - 1202.
6) A. J. Koivo and G. A. Bekey, "Report of Workshop on Coordinated Multiple Robot Manipulators : Planning, Control and Application," IEEE Journal of Robotics and Automation, Vol. RA-4, No.1, 1988, pp. 91 - 93.
7) A. Ahmad and S. Luo, "Coordinated Motion Control of Multiple Robotic Devices for Welding and Redundancy Coordination through Constrained Optimization in cartesian space," IEEE Journal of Robotics and Automation, Vol. RA-5, No. 4, 1989. pp. 409 - 417.
8) C. R. Carignan and D. L. Akin, "Cooperative Control of Two Arms in the Transport of an Inertial Load in Zero Gravity," IEEE Journal of Robotics and Automation, Vol. RA - 4, No, 4. 1988, pp. 414 - 418
9) H. Seraji, "Coordinated Adaptive Position/Force Control of Dual-Arm Robots," IASTED Int'l Journal of Robotics and Automation, Vol. 3, No. 3, 1988, pp. 140 149.
10) C. O. Alford and S.M. Belyen, "coordinated Control of Two Robot Arms," Proc. of IEEE Int'l Conf. on Robotics and Automation, 1984, pp. 468 - 473.
11) P. Ro and K. Youcef toumi, "A Robust Motion Coordination of Two Dynamically Interacting Systems," Proc. of ASME WAM89, San Francisco, Dec. 1989.
12) P. Ro and K. Youcef - Toumi, "A Robust Motion Coordination of Two Dynamically Interacting Systems with Model Uncertainties and Bounded Disturbances," Proc. of 28th IEEE Conf. on Decision and Control, Tampa, Dec. 1989.
13) M. Cotsaftis and C. Vibet, "Decoupled Control for 2 D N Link Biped Walking System", Robotics and Autonomous Systems 5, pp. 97 - 107, 1989.
14) P. L. Falb and W. A. Wolovich, "Decoupling in the Design and Synthesis of Multivariable Control Systems," IEEE Trans. on Automatic Control, Vol. AC 12, No. 6, Dec. 1967.

15) M. A. Unseren and A. J. Koivo, "Reduced Order Model and Decoupled Control Architecture for Two Manipulators Holding an Object," Proc. of IEEE Conf. on Robotics amd Automation, 1989, pp. 1240 - 1245.

16) Choi, H. S. and Ro, P. I., "An Adaptive Two-Arm Control of Object Transport with Parameter Uncertainties," ASME Winter Annual Meeting, CA., pp. 227 - 228, 1992.