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A Closed-Chain Jacobian-Based Hybrid Control for Two Cooperating Arms with a Passive Joint : An Application to Sawing Task

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Abstract

This work deals with a sawing task performed by two cooperating arms. For the sawing task to follow a line in a horizontal plane, three directional motions have to be controlled (i.e., two translational motions and one rotational motion). Also, a certain level of force has to be controlled toward the vertical direction not to loose the contact with the object to be sawn. The two-arm system under our hand consists of a four degree-of-freedom SCARA robot and a five degree-of-freedom PT200V robot. When the two arms are rigidly grasping a saw, the mobility of the system is 3, which is not enough for sawing tasks. Therefore, we deliberately insert a passive joint at the end of the SCARA robot to increase the mobility up to 4. A hybrid control method to regulate the force and position by the two arms is proposed in this work. The proposed scheme has three typical features ; first, the two arms are treated as one arm in a kinematic viewpoint. Secondly, our approach is different from other acceleration-based approach, in the sense that our hybrid control method is based on a Jacobian and an internal kinematics for a single closed-kinematic chain of the two arms to reflect the nature of the position-controlled industrial manipulator. Thirdly, the proposed scheme is not only able to operate the system even if a passive joint exists, but also is able to utilize the internal loads for useful applications such as pitch motion control. We experimentally show that the performance of the position and force response are satisfactory, and that one additional passive joint not only prevents the system from unwanted roll motion in the sawing task, but also allows an unwanted pitch motion to be notably reduced by an internal load control.

1. Introduction

Current industrial robot manipulators are position-controlled devices. This implies that the force cannot be directly controlled by actuators, but is indirectly controlled by measuring the force error and compliantly adjusting the end-position of the manipulator. The so-called, compliance control schemes[4,6,7] have been employed in the control of a single robot in contact with its environment. Most of works on this subject led to the introduction of the hybrid position/force control system [1,9,10,12,13]. Basic examples of those tasks include scraping, grinding, polishing, and sawing.

Multiple cooperating robots can perform many tasks which cannot be carried out by using a single arm. As control methods for multiple arms, master/slave scheme and non-master/slave scheme have been proposed. Tao and Luh *et al.*[4] considered a compliant coordination control of two robots employing master/slave scheme. Their application was an assembly operation between a bolt and nut. Kosuge *et al.*[7] proposed a decentralized control scheme of dual arms. To execute the task in a decentralized way, the motion of the object is given to the leader, and the follower estimates the motion of the leader based on the information from its own force sensors. However, it has been known from the previous practices that master/slave approach suffers from time delay in force tracking, because knowledge of the desired position is only accessible for the master, and that this scheme does not actually represent load distribution between two arms. In order to overcome these drawbacks, Fujii and Kurono[8] have proposed a non-master/slave scheme. Their method first defines position/orientation reference to the object, from which position/orientation references to the hands of the two robots are calculated. Next, they introduced a compliance control technique for the coordination of the two robots. By introducing the technique, however, they lost the accuracy of positioning of the object. To resolve this problem, Uchiyama *et al.* [9] proposed a symmetric hybrid position/force control scheme for the coordination of two arms. Here, their scheme is symmetric in the sense that the workspace vectors defined are symmetric functions of the joint space vectors of the two robots. In their scheme, two arms equipped with force/torque sensor at each wrist simultaneously regulate force and position.

Bonitz and Hsia[11] proposed a internal force-based impedance control for cooperating two arms. Their algorithm was successfully applied to the internal force control for the grasped object. However, previous works on multiple arms have treated only parallel manipulators which consist of several identical manipulators. Also, the case that some of the joint actuators of multiple arms are not activated has not been considered yet.

In this work, we propose a hybrid control method for sawing task using two arms. The proposed scheme has three typical features; first, the two arms are treated as one arm in a kinematic viewpoint. This approach is quite useful when dealing with the kinematics, dynamics, and control of a two-arm system with general kinematic structure. Secondly, our approach is different from other acceleration-based approach in the sense that our hybrid control method is based on a Jacobian and an internal kinematics for a single closed-kinematic chain of the two arms to reflect the nature of the position-controlled industrial manipulator. Thirdly, the proposed scheme is not only able to operate the system even if a passive joint exists, but also able to utilize the internal loads for useful applications such as pitch motion control. The two-arm system under our hand consists of a four degree-of-freedom SCARA robot and a five degree-of-freedom PT200 robot. The mobility of the system is 3, which is not enough to control three positional variables and one force variable. Therefore, in order to increase the mobility of the system up to 4, we deliberately insert a passive joint at the end of the SCARA robot. We experimentally show that the performance of the position and force response are satisfactory, and that one additional passive joint not only prevents the system from unwanted roll motion in the sawing task, but also allows an unwanted pitch motion to be notably reduced by an internal load control.

2. Sawing Task by Two Cooperating Arms

In the sawing task, the trajectory of the saw grasped by the two arms is first planned in an offline fashion. When the trajectory is planned to follow a line in a horizontal plane, three directional motions have to be controlled (*i.e.*, two translational motions and one rotational motion). Also, a certain level of force has to be controlled toward the vertical direction(*i.e.*, minus z-direction) not to loose the contact with the object to be sawn. A typical feature of the sawing task is that the contact position is continuously changing. Therefore, the kinematic mapping between the force-controlled position and the joint actuators has to be updated continuously.

Figure 1 represents our two-arm system which consists a four degree-of-freedom SCARA robot and a 5 degree-of-freedom PT200 robot. Mobility of a manipulator is equal to the number of independent variables which can be specified to locate all members of the mechanism relative to one another. Assume that J, L, F_i, and C denote the numbers of joints, links, degree-of-freedom of each joint, and the maximum degree of freedom of each link (6 for spatial motion and 3 for planar or spherical motion), respectively. Then, according to the mobility equation, given by

$$D = C(L-1) - \sum_{i=1}^{J}(C - F_i) \quad (1)$$

the mobility of our two-arm system is 3 where the two arms are rigidly grasping a saw. Since it is not enough to control three positional variables and one force variable, we deliberately insert a passive revolute joint at the end of the SCARA robot such that the direction of the axis is parallel to the y axis of the saw coordinate system, as shown in Fig. 2, to increase the mobility of the system up to 4. In our experiment, we demonstrate that the additional passive joint plays an important role.

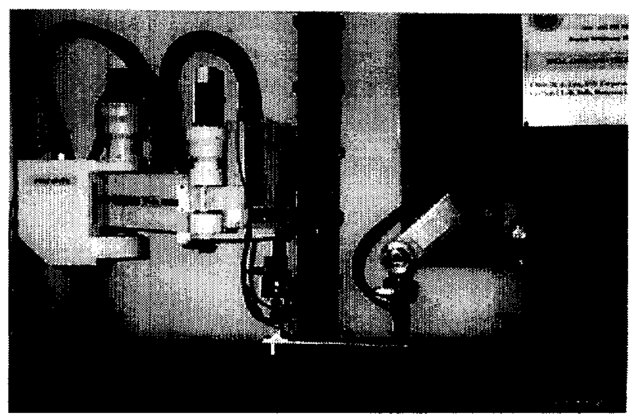

Fig.1. Experimental Set-up for Sawing Task.

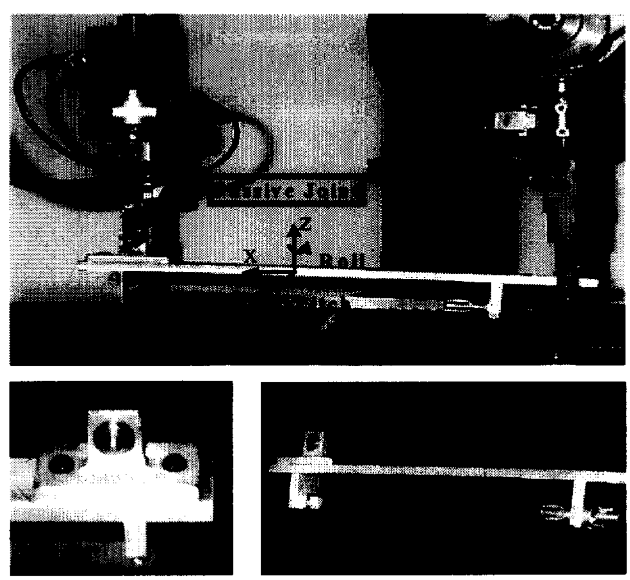

Fig.2. A Passive Joint and the Saw

3. Kinematic Modeling of Two Arms

The kinematics of general closed-chain systems such as multiple arms or dual arms is divided into two layers[5]. The first layer describes the internal relationship between the *independent* joint set and the *dependent* joint set. The second layer deals with relationship between the end-effector motion coordinates and the independent set of actuator coordinates.

3.1 Internal Kinematics

The following discusses internal kinematics of dual arms which consist of two serial chains connected to (or holding) a common object moving in a N-dimensional operation space. Each chain may have different number of joint. Since each arm has a common higher-order kinematics such as velocity and acceleration at the end-effector coordinate, the end-effector coordinate is here chosen as an intermediate coordinate set to determine the internal kinematic relationship.

The velocity vector of the end-effector ($\dot{u}$) can be expressed directly in terms of the joint velocity vector (${}_r\dot{\phi}$) of the r^{th} open-chain structure, according to

$$\dot{u} = [{}_rJ]\,{}_r\dot{\phi} \qquad r = 1, 2, \tag{2}$$

where $[{}_rJ]$ denotes the first-order kinematic influence coefficient(KIC) matrix (or Jacobian) relating the end-effector coordinate vector to the joint coordinate vector. Eq.(2) implies that there are N algebraic equations relating one of the joint velocity set to the other set. This can be expressed as

$$[{}_1J]\,{}_1\dot{\phi} = [{}_2J]\,{}_2\dot{\phi}. \tag{3}$$

Now, Eq.(3) can be rearranged and regrouped according to the independent and dependent coordinate velocity sets of each chain as

$$\left[{}_1J_a\right]{}_1\dot{\phi}_a + \left[{}_1J_p\right]{}_1\dot{\phi}_p = \left[{}_2J_a\right]{}_2\dot{\phi}_a + \left[{}_2J_p\right]{}_2\dot{\phi}_p. \tag{4}$$

Then, Eq.(4) is augmented into single matrix equation, given by

$$[A]\,\dot{\phi}_p = [B]\,\dot{\phi}_a, \tag{5}$$

where

$$[A] = \left[\left[{}_1J_p\right] : -\left[{}_2J_p\right]\right], \tag{6}$$

and

$$[B] = \left[-\left[{}_1J_a\right] \ : \ \left[{}_2J_a\right]\right]. \tag{7}$$

Assume that M_r denotes the number of joint (or mobility) of r^{th} open-chain. Then, in Eqs. (4) and (5), $\dot{\phi}_a$ and $\dot{\phi}_p$, respectively, denotes the M dimensional independent joint velocity vector and the $(M_1 + M_2 - M)$ dimensional dependent joint velocity vector. $[A]$ and $[B]$ implies the $(M_1 + M_2 - M) \times (M_1 + M_2 - M)$ and $(M \times M)$ matrices, respectively.

Therefore, direct inversion of the square matrix $[A]$, which is assumed to be nonsingular, gives

$$\dot{\phi}_p = [A]^{-1}[B]\,\dot{\phi}_a = \left[G_a^p\right]\dot{\phi}_a, \tag{8}$$

where $\left[G_a^p\right]$ of dimension $(M_1 + M_2 - M) \times M$ denotes the first-order internal kinematic influence coefficient (IKIC) matrix of the dual arm system. Assuming that ϕ represents the whole joint set of the system, the relationship between the independent joint set and the whole joint set is expressed as

$$\dot{\phi} = \left[G_a^\phi\right]\dot{\phi}_a, \tag{9}$$

where $\left[G_a^\phi\right]$ of dimension $M_t (= M_1 + M_2) \times M$ is obtained as below

$$\left[G_a^\phi\right] = \begin{bmatrix} [I] \\ \left[G_a^p\right] \end{bmatrix}. \tag{10}$$

3.2 Forward Kinematics

Since joints of the r^{th} chain $({}_r\phi)$ are composed of some of the independent and dependent joints, ${}_r\dot{\phi}$ can be expressed in terms of the independent joints of the system as given by

$${}_r\dot{\phi} = \begin{bmatrix} {}_r\dot{\phi}_a \\ {}_r\dot{\phi}_p \end{bmatrix} = \left[{}_rG_a^\phi\right]\dot{\phi}_a, \tag{11}$$

where $\left[{}_rG_a^\phi\right]$ is obtained by augmenting the elements of Eq. (8) into ${}_r\dot{\phi}_p$. Thus, the forward kinematics for the common object is finally obtained by plugging the first-order IKIC into one of the open-chain kinematic expressions as follows :

$$\dot{u} = \left[{}_rJ\right]{}_r\dot{\phi} = \left[G_a^u\right]\dot{\phi}_a, \tag{12}$$

where

$$\left[G_a^u\right] = \left[{}_rJ\right]\left[{}_rG_a^\phi\right]. \tag{13}$$

It is remarked that the methodology introduced in this section can be applied not only to two arms, but also to general multiple arms.

4. Force Control Algorithm for Sawing Task

In this section, a general compliance model for general two-arm system is developed and it is applied to the force control in the sawing task. In the sawing task, a certain level of force has to be controlled toward the vertical direction(i.e., minus z-direction) not to loose the contact with the object to be sawn.

Note that the dimensions of $\dot{u}$ and $[G_a^u]$ are 6×1 and 6×4, respectively, in three-dimensional space. Since only the force along the z-direction is controlled in the sawing task, a Jacobian which relates the force vector, δF, to the joint minimum actuators is given as

$$\delta T_a = [J_1]^T \delta F \tag{14}$$

where $[J_1]$ denotes a matrix of dimension of 3×4, formed by collecting the first, second, and the third rows of $[G_a^u]$. Note that the force control in the sawing task is different from those in previous works[1,2,9,10,11], in that the contact position is continuously changing. We resolve this problem by continuously updating the kinematic mapping $[J_1]$ according to the position information of the system.

The dynamics of general closed-chain manipulator can be represented in terms of a minimum(independent) coordinate set being equal in number to the minimum number of inputs(i.e., mobility) required to completely describe the system kinematics.

Recalling Newton's second law of motion, the effective inertial load T_a^* of the system, referenced to a set of independent joints, is described in terms of the system's effort sources (T_a and T_p), externally applied loads (T_u^L), and effective gravity loads (T_ϕ^G) as follows :

$$T_a^* = \left[G_{a_1}^\phi\right]^T T_\phi - \left[J_1\right]^T T_u^L + \left[G_{a_1}^\phi\right]^T T_\phi^G, \tag{15}$$

where $[G_{a_1}^\phi]$ denotes the matrix excluding the row corresponding to the additional passive joint from $[G_a^\phi]$, since the passive joint cannot be activated, and we define

$$T_\phi = \begin{bmatrix} T_a \\ T_p \end{bmatrix}, \tag{16}$$

$$T_a^* = \left[G_{a_1}^\phi\right]^T T_\phi^*, \tag{17}$$

$$T_\phi^* = \left[\left({}_1T_\phi^*\right)^T \left({}_2T_\phi^*\right)^T\right]^T, \tag{18}$$

$$T_\phi^G = \left[\left({}_1T_\phi^G\right)^T \left({}_2T_\phi^G\right)^T\right]^T, \tag{19}$$

and

$${}_rT_\phi^G = \sum_{i=1}^{M_i} \left[{}_r^iG_\phi^c\right]^T {}_r^iF_G \quad r = 1, 2. \tag{20}$$

The inertial load and gravity loads, referenced to the independent input set, are obtained from the open-chain dynamics via a virtual work-based transfer method employing $[G_a^\phi]^T$. T_a and T_p denote the efforts of the independent and dependent joints, respectively. T_ϕ denotes the effort of the total joints. T_u^L is an external load applied to the object coordinated u. ${}_r^iF_G$ is the gravity load acting on the center of gravity of the *ith* link of the *rth* chain, and ${}_rT_\phi^*$ and ${}_rT_\phi^G$ are the total effective inertial and gravity loads of the *rth* chain referenced to the inputs of the *rth* chain, respectively. The matrix $[{}_r^iG_\phi^c]$ is the Jacobian that relates the mass center of the *ith* link of the *rth* chain to the inputs of the *rth* chain.

Now, consider that the system is in a state of equilibrium. For this, the effective load referenced to the independent joints must be zero, that is,

$$T_a^* = \left[G_{a_1}^\phi\right]^T T_\phi - \left[J_1\right]^T T_u^L + \left[G_{a_1}^\phi\right]^T T_\phi^G = 0. \tag{21}$$

Assuming that only minimum actuators are activated, Eq.(21) can be equivalently expressed as

$$T_a = \left[J_1\right]^T T_u^L - \left[G_{a_1}^\phi\right]^T T_\phi^G, \tag{22}$$

and a linearized form of Eq. (22) is obtained as

$$\delta T_a = \left[J_1\right]^T \delta(T_u^L) + (T_u^L)^T \left[\frac{\partial [J_1]^T}{\partial \phi_a} \delta\phi_a\right] - \left[G_{a_1}^\phi\right]^T \delta(T_\phi^G) - (T_\phi^G)^T \left[\frac{\partial [G_{a_1}^\phi]^T}{\partial \phi_a} \delta\phi_a\right]. \tag{23}$$

Given an external disturbance to system, the resulting behavior can now be modeled as a spring action with respect to independent inputs of the system. Thus, the system stiffness equation is obtained by differentiating both sides of Eq. (23) with respect to ϕ_a as follows :

$$[K_{aa}] = -\frac{\partial T_a}{\partial \phi_a} = [J_1]^T[K_{uu}][J_1] - T_u \frac{\partial [J_1]^T}{\partial \phi_a} - [G_{a_1}^\phi]^T[V][G_{a_1}^\phi] + T_\phi^G \frac{\partial [G_{a_1}^\phi]^T}{\partial \phi_a}, \tag{24}$$

since the following actions hold :

$$\delta T_a = -[K_{aa}]\delta\phi_a, \tag{25}$$

$$\delta T_u^L = -[K_{uu}]\delta u, \tag{26}$$

and

$$\delta T_\phi^G = -[V]\delta\phi, \tag{27}$$

where $[V]$ is a $M_t \times M_t$ block diagonal matrix, each block diagonal element of which is given by

$$[V_r] = \sum_{i=1}^{M_i} \frac{\partial \left[{}_r^iG_\phi^c\right]^T}{\partial_r \phi} ({}_r^iF_G), \quad r = 1, 2. \tag{28}$$

The second term, and the third and fourth term of right-side of Eq. (24) denote additional stiffness effects due to the external applied loads and gravity loads, respectively. On the other hand, compliance matrix referenced to the minimum input can be expressed as

$$[C_{aa}] = [K_{aa}]^{-1} . \tag{29}$$

In the case of full actuation, the effective effort at the minimum actuator site is given by

$$T_a = [G_a^{\phi}]^T T_{\phi} \tag{30}$$

with the differential relation expressed as

$$\delta T_a = [G_a^{\phi}]^T \delta T_{\phi} . \tag{31}$$

For an infinitesimal motion, the equivalent kinematic model of Eq. (9) is given by

$$\delta\phi = [G_a^{\phi}] \delta\phi_a \tag{32}$$

where $\delta\phi$ and $\delta\phi_a$ can be represented by the following relations

$$\delta\phi = -[C_{\phi\phi}] \delta T_{\phi} , \tag{33}$$

and

$$\delta\phi_a = -[C_{aa}] \delta T_a . \tag{34}$$

Substituting Eq. (31) into Eq. (34), and Eqs. (33) and (34) into Eq. (32) yield a compliance relationship between the total actuator coordinates and the minimum actuator coordinates given as

$$[C_{\phi\phi}] = [G_{a_1}^{\phi}][C_{aa}][G_{a_1}^{\phi}]^T . \tag{35}$$

For a very hard environment, the stiffness $[K_{uu}]$ of the environment is very large compared to the additional stiffness effects due to the externally applied force, gravity loads, and joint loads as seen from Eq.(24), therefore Eq. (35) can be simplified as

$$[C_{\phi\phi}] = [G_a^{\phi}][J_1]^+ [K_{uu}]^{-1} ([J_1]^T)^+ [G_a^{\phi}]^T . \tag{36}$$

where $[J_1]^+$ and $([J_1]^T)^+$ denote the pseudo-inverse solutions of $[J_1]$ and $[J_1]^T$, respectively, and the dimension of $[K_{uu}]$ in the sawing task is 3×3 .

Figure 3 represents a block diagram of the proposed controller. A simple PID controller is employed to compensate for the measured force error δF and to maintain a good force response. Then, for the compensated force error $\delta F'$, the effort (δT_a) at the minimum input locations is computed as

$$\delta T_a = [J_1]^T \delta F' , \tag{37}$$

and then, according to the general solution of Eq. (31), given by

$$\delta T_{\phi} = ([G_a^{\phi}]^T)^+ \delta T_a + ([I] - ([G_a^{\phi}]^T)^+ [G_a^{\phi}]^T) \varepsilon , \tag{38}$$

the effort (δT_{ϕ}) at the total input locations is calculated only by using the first term of Eq. (38). In Eq. (38), $([G_a^{\phi}]^T)^+$ denotes the pseudo-inverse solution of $[G_a^{\phi}]^T$. While the first-term of Eq. (38) denotes a minimum norm solution, the second-term represents a homogeneous solution creating an internal loading.

In particular, the homogeneous solution offers chances of several subtasks. Though both joint-based method and object-based method can be considered in the control of the internal load state, we employ a joint-based load distribution scheme due to its applicability to general kinematic and actuation configuration[16].

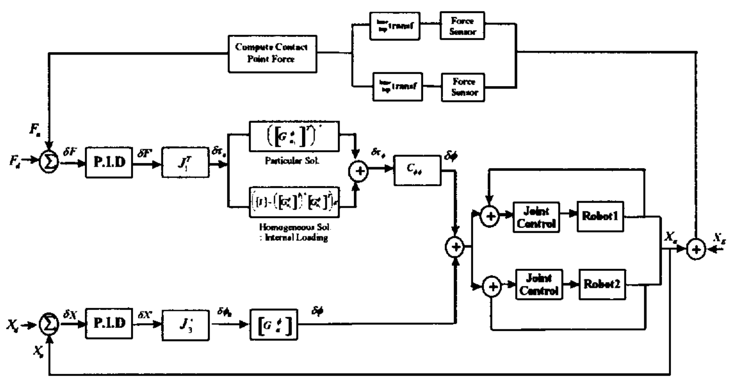

Fig.3. Block Diagram of the Proposed Hybrid Control Scheme.

The proposed approach is based on imposing constraints on the joint space variables. Specifically, we consider constraints of the form [5,16]

$$[G(\phi)]\delta T_{\phi} = \alpha \tag{39}$$

where $[G(\phi)] \in \Re^{(M_t - M) \times M_t}$, and α is a known (time dependent) vector (recall that M is the mobility of the dual arm system). The constraints in Eq. (39), represented by the row of **G** and the corresponding elements in α , are independent of each other. This implies that **G** must have full rank. **G** and α are to be selected according to the type of subtask to be performed and represent the criteria to be used in distributing the manipulator loads.

Assuming this has been accomplished, we wish to choose ε in Eq. (38) to satisfy the minimum norm solution as well as the additional subtask described in Eq. (39). Let T' be defined as the first-term of Eq. (38). Substitute Eq. (38) into Eq. (39) to obtain

$$[G]T' + [G]\Big[[I] - \big([G_a^*]^T\big)^+[G_a^*]^T\Big] = \alpha \quad (40)$$

or

$$[H]\,\varepsilon = \alpha - [G]T' \quad (41)$$

where

$$[H] = [G]\Big[[I] - \big([G_a^*]^T\big)^+[G_a^*]^T\Big]. \quad (42)$$

Now, the choice of

$$\varepsilon = [H]^+\big(\alpha - [G]\,T'\big) \quad (43)$$

provides the minimum norm solution and the constraint Eq.(39). Here, $[H]^+$ denotes the pseudo-inverse solution of $[H]$.

There will be many different choices of possible [G] in Eq. (39). In our experimental work, we utilize the internal loading to eliminate unwanted pitch motion which can be created by moment-unbalancing along the y (or pitch) direction during the sawing task(refer to Fig.2). Now, we derive a force relationship between the minimum actuator coordinates and moment vector at the contact position.From Eq.(12), the angular velocity vector ω of the saw is obtained as

$$\omega = [J_2]\,\dot{\phi}_a \quad (44)$$

where $[J_2]$ denotes the matrix formed by collecting 4th, 5th, and 6th row vectors of $[G_a^*]$. Now, from the duality relation between the force and velocity vectors, we have

$$T_a = [J_2]^T\, m \quad (45)$$

where m denotes the moment vector at the contact point. Assuming that $[J_2]$ is not singular, the moment vector is given as

$$m = \big([J_2]^T\big)^+ T_a = \big([J_2]^T\big)^+[G_a^*]^T T_\phi = [P]\,T_\phi \quad (46)$$

Now, since we desire the moment about the y-axis to be kept zero regardless of the sawing motion, we decide [G] and α as

$$[G] = [P]_{2;}, \quad \alpha = 0 \quad (47)$$

where $[P]_{2;}$ denotes the second row of $[G]$ and α is a scalar. Besides the above example, more complex criteria involving groups of actuators can be possibly incorporated[5,16].

Now, according to the compliance relation of Eq. (36), the joint angles are adjusted such that the force error can be eliminated.

5. Position Control for Sawing Task

In general, the sawing task is performed along a straight line in a plane. For this task, we need to control the translational motions along the x and y directions and the rotational motion about the z-axis.

A Jacobian which relates the velocity vector for those three motions to the velocity vector for minimum actuators is given as

$$v = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \omega_z \end{bmatrix} = [J_3]\,\dot{\phi}_a \quad (48)$$

where $[J_3]$ denotes a matrix of dimension of 3×4, formed by collecting the first, second, and the sixth rows of $[G_a^*]$.

For a given trajectory of the saw, $\dot{\phi}_a$ is obtained according to

$$\dot{\phi}_a = [J_3]^+\, v \quad (49)$$

where $[J_3]^+$ denotes the pseudo-inverse of $[J_3]$, and then the velocity of all joints are determined from Eq. (9). Every joints except the passive joint are driven by each joint motor. Though only the minimum actuators can generate the motion, the redundant joints take the role of load sharing for motion. In that sense, the passive joint does not participate in the load sharing, but just moves dependently of the minimum joints due to the nature of the closed kinematic chain of the two-arm system. A simple PID position controller is employed to compensate for the position error and also to maintain a good position response.

6. Experimental Results

Sawing experiments have been performed by using two arms with an additional passive joint; one 4-axis SCARA robot and one 5-axis articulated industrial robot manipulator (PT200V). In this configuration, the mobility is 4 according to Eq.(1). Therefore, the four axes from the base of PT200V robot are chosen as the independent joint set, although there are many potential independent joint sets.

Each robot is equipped with a force sensor at its end-point. The interaction force and moment between the dual arms and the environment can be measured using two F/T sensors attached to the end of each robot. Our control scheme is written in C-language and tested in our prototype dual robot controller[3]. Two 32-bit microprocessor boards(FORCE30[15], KVME040) are used. One board is a main CPU board for trajectory generation, each joint control, user interface, *etc.* The other one is employed as a sensor CPU board for raw sensor data acquisition from sensor, sensor data handling, transmitting control data to the main CPU board, *etc.* According to time analysis, it takes 64 msec for trajectory generation, during which motion generation costs 30 msec and user interface needs 34 msec. On the other hand, in the force control applications by the two arms, the other CPU board is used for manipulation of sensor data.

Note that satisfactory performances can be obtained only under the condition that the actual environmental stiffness value is exactly given by an operator. In most practical cases, exact environmental stiffness values are not known in advance and thus they should be automatically measured or estimated as a robot contacts with unknown environments. In order to estimate the unknown or changing magnitude of the environmental stiffness, many researchers have proposed several sophisticated approaches [6] which employ robot dynamics and adaptation method. In this work, we estimate the magnitude of the environmental stiffness, experimentally, by measuring the force for an induced displacement against the environment[2]. The stiffness magnitude of the object to be sawn has been experimentally measured as 35000 N/m.

In the sawing task, a desired force to be controlled is given 10 Newtons along the vertical direction of the environment surface. The motion of the saw is controlled to have periodic motion in the x-direction. Fig. 4 shows the roll motion(rotational motion about the z-axis of Fig.2) when the additional passive joint is not included. This roll motion is not desirable since it keeps the saw from following a straight-line motion. On the other hand, Fig. 5 shows that the unwanted roll motion can be eliminated by including a passive joint to the system. A small perturbation is observed at each moment that the motion of the saw is reversed. This may be due to the backlash existing in the two-arm system. Also, an internal load control to suppress an unwanted pitch motion (rotational motion about the y-axis of Fig.2) have been considered. Without consideration of the internal load control algorithm derived in the section 4, a periodic pitch motion occurs in the sawing task, as shown in Fig. 6. In the meanwhile, with consideration of the internal load control algorithm, the pitch motion can be notably reduced as shown in Fig. 7.

The remaining pitch motion of Fig. 7 may be caused by the dynamic motion of the saw. Finally, Fig. 8 and Fig. 9 demonstrate the force and position responses for our proposed scheme, respectively. It is observed that the saw follows the desired trajectories satisfactorily in both position- and force-level.

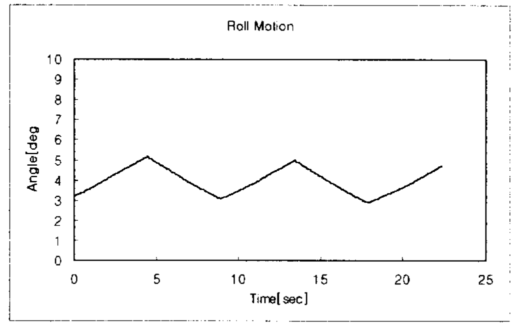

Fig.4. Roll Motion when an Additional Passive Joint is not included.

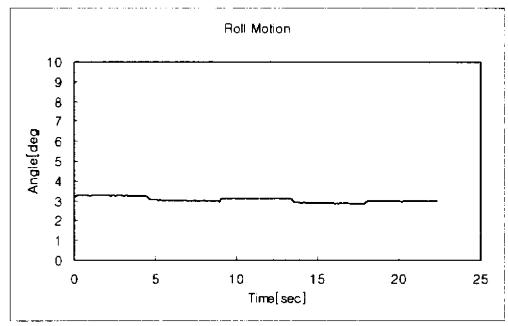

Fig. 5. Roll Motion when a Passive Joint is included.

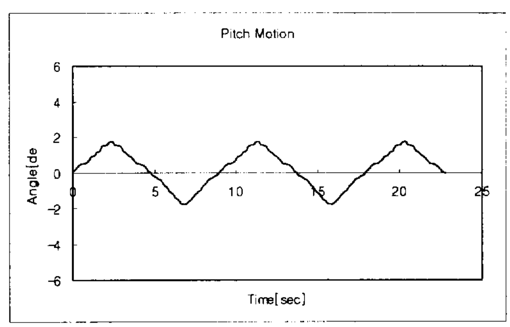

Fig.6. Pitch Motion without Consideration of Internal Load Control.

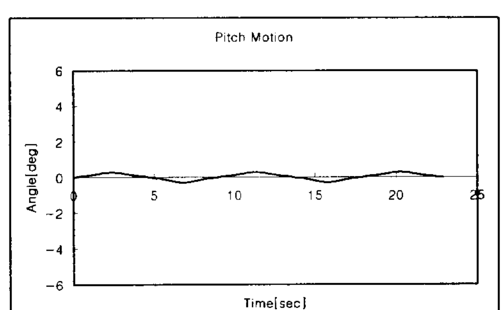

Fig.7. Pitch Motion with Consideration of the Internal Load Control.

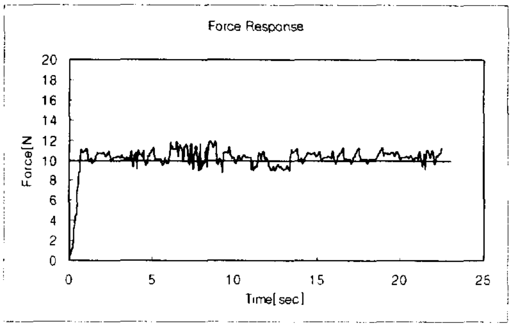

Fig.8. Force Control (10N : desired) in the Sawing Task.

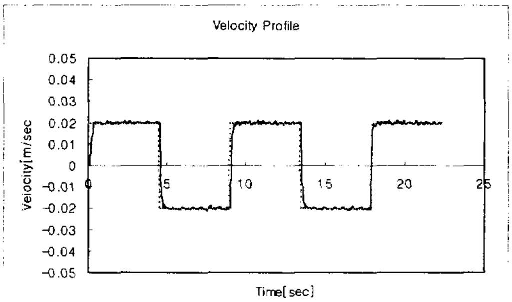

Fig.9. Velocity Control (dashed line : desired) in the Sawing Task.

7. Conclusions

In this work, we propose a hybrid control method for sawing task using two arms with an additional passive joint. The proposed scheme is able to treat the kinematics, dynamics, and control of a two-arm system with general kinematic structure, and it is different from other acceleration-based approach in the sense that our hybrid control method is based on a Jacobian and an internal kinematics for a single closed-kinematic chain of the two arms to reflect the nature of the position-controlled industrial manipulator. Also, the proposed scheme is not only able to operate the system even if a passive joint exists, but also able to utilize the internal loads for useful applications such as pitch motion control. We experimentally show that by inserting a passive joint to the two-arm system, the proposed control scheme is able to keep the system form the unwanted roll motion and unwanted pitch motion in the sawing task as well as yields a satisfactory performances in the position and force responses.

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