A SYMMETRIC HYBRID POSITION/FORCE CONTROL SCHEME FOR THE COORDINATION OF TWO ROBOTS

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Abstract

Coordination of two robots to manipulate a single object jointly, needs a certain form of hybrid position/force control. In this paper, a non-master/slave scheme, called symmetric scheme is proposed for the coordination. The definition of workspace force, velocity and position vectors as symmetric functions of the jointspace force, velocity and position vectors of the two robots is essential to implementing the symmetric scheme. These workspace vectors are derived by first analyzing the statics of the closed kinematic chain consisting of the two robots and the object, and then calculating velocities using the force-velocity duality; finally, the workspace position vector is defined by integrating the velocities. The derived workspace vectors are used successfully to implement the symmetric scheme.

1. Introduction

To have two arms on a robot is as important as on a man, in particular, for applying the robot to tasks in unstructured environments such as space or ocean. The use of two arms on a robot makes it possible to perform various kinds of sophisticated tasks, such as handling large, heavy, or non-rigid objects [1], or modifying the grasping position of an object [2]. These applications require solving complex problems such as the analysis of a closed chain [3], [4], the description of the tasks [5], synchronization of the robots [6], or collision avoidance [7].

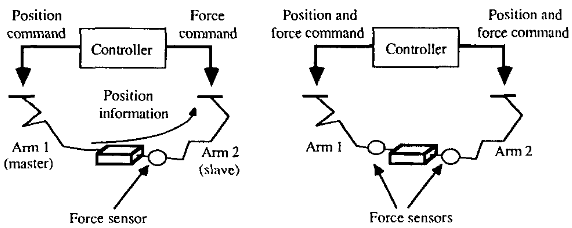
The force/compliance control is a fundamental feature in using two robots handling a same object [8]-[13]. It permits compensating the positioning errors of the robots which induce constraints in the object. However, there is an issue on force/compliance control to be considered. The issue is on which is more advantageous: a master/slave scheme or non-master/slave scheme. This has been discussed very briefly by Mason [14].

In the master/slave scheme, the force-controlled slave arm follows the position-controlled master arm [8]. The position of the slave arm is determined by the position of the master arm. Therefore, the impedance of the slave arm has to be very small to follow the motion of the master arm. To realize force control with small impedance, however, is still under tough research. This is one of the serious problems which this scheme has. Another problem is how to assign master and slave modes to the arms. The master arm and the slave arm have to change their roles in the process of performing tasks.

These dificulties come from the fact that the slave arm obtains the information for positioning through its force sensor only. This is illustrated in Figure 1 (a). If we suppose that the two arms have a unique central controller - like a human brain, position reference to the object should be equally used for the positioning of the both arms as illustrated in Figure 1 (b). This would be a reason why a more natural undistinguished scheme, namely a non-master/salve scheme has been sought by many researchers [9], [11]-[13].

Fujii and Kurono have proposed a non-master/slave scheme [9]. 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.

In order to solve this problem, Uchiyama et al. [11] proposed a non-master/slave hybrid position/force control scheme in which the workspace position vector is defined as the combination of the absolute position/orientation of the object plus the relative position/orientation between the hands. They have shown successfull experimental results, but have given no theoretical elaboration on the coupled kinematic system consisting of the two arms and the object.



(a) Master/slave control (b) Non-master/slave control

Figure 1: Master/slave and Non-master/slave control schemes

Recently the authors have proposed a general kinematic formulation for the description of the tasks [12], [13]. They have given theoretical derivation of workspace coordinates for two robots working on a same object. The theory presented in this formulation complements the experiment done by Uchiyama et al. [11].

In this paper, according to the theory, we give a thorough set of static and kinematic equations for the system and present a symmetric non-master/slave hybrid position/force coordinated control scheme using the equations. The equations are symmetric in the sense that the workspace vectors defined are symmetric functions of the jointspace vecotrs of the two robots. The control scheme is a natural extension of the hybrid position/force control scheme for a single arm robot.

In deriving the equations, we pay first attention to static relationship in two robots holding a single object and analyze this relationship by introducing a concept of "virtual stick". The virtual stick is an imaginary stick which is fixed to the hand of each robot and goes to the center of the object. The stick is supposed to be rigid. The static relationship is simplified dramatically by using the concept of this virtual stick. We define external and internal forces/moments by applying matrix pseudoinverse techniques to the static relationship.

Corresponding to the external and the internal forces/moments, respectively, we define the absolute velocity of the object and the relative velocity between the two hands using the principle of virtual work. The integration of the absolute and the relative velocities gives the absolute and the relative positions/orientations, which we use as workspace coordinates to describe the coordinated tasks. The derivation of the direct and differential kinematic equations between this workspace and the jointspace of the two robots is straightforward.

The organization of this paper is as follows. Initially, we elaborate statics and kinematics of two robots working on a same object and define workspace vectors to describe the tasks done by the two robots. Next, we show the organization of the symmetric control scheme using the defined workspace vectors. At the end of this paper, we give conclusions and suggestions for future work.

2. Workspace Vectors Describing Coordinated Tasks

2.1 Workspace Force Vectors

Let us consider two robots holding an object as shown in Figure 2. The two robots exert forces and moments: ${}^o\mathbf{F}_{h1}$, ${}^o\mathbf{N}_{h1}$ and ${}^o\mathbf{F}_{h2}$, ${}^o\mathbf{N}_{h2}$, at O_{h1} and O_{h2} through the hands 1 and 2, respectively. We suppose that the robots can exert both force and moment on the object. Throughout this paper, the prefix of a vector represents the frame with respect to which the vector is represented.

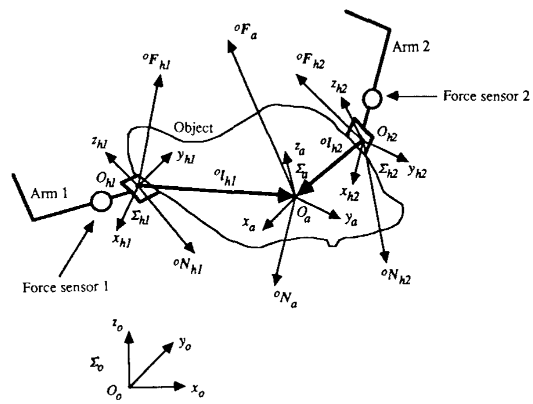


Figure 2: Static relation in two robots holding an object

Therefore the prefix o means that the vector is represented with respect to the base frame $\Sigma_o(O_o-x_oy_oz_o)$. To show the frame explicitly with respect to which a vector is represented is important since we will represent the same vector with respect to a different frame as in Section 2.4.

The vectors ${}^o\mathbf{l}_{h1}$ and ${}^o\mathbf{l}_{h2}$ from O_{h1} to O_a and O_{h2} to O_a, respectively, are determined at the moment when the two robots hold the object if O_a on the object is defined. We assume that the vectors are like rigid sticks fixed to the hands. We call this vector like a stick a virtual stick. The virtual stick is a key concept of this paper. Since the sticks are rigid and fixed to the hands, the tips of the sticks do not point to O_a any more in case the object deforms or the hands slip on the object. Throughout this paper, we suppose that the deformation and the slippage are very small.

The force and moment ${}^o\mathbf{F}_{bi}$ and ${}^o\mathbf{N}_{bi}$ at the tip of the virtual stick are calculated from the force and moment ${}^o\mathbf{F}_{hi}$ and ${}^o\mathbf{N}_{hi}$ at the root of the virtual stick as follows:

$$ {}^o\mathbf{F}_{bi}={}^o\mathbf{F}_{hi} \tag{1}$$

$$ {}^o\mathbf{N}_{bi}={}^o\mathbf{N}_{hi}+{}^o\mathbf{F}_{hi}\times{}^o\mathbf{l}_{hi} \tag{2}$$

where i=1 and 2. Throughout this paper, the suffix i represents the numbers 1 and 2, meaning that the quantity with the suffix represents that of the robot i.

If we suppose that the tips of the two virtual sticks are at the the same point O_a, the resultant force and moment on the object at O_a caused by the forces and the moments are given by

$$ {}^o\mathbf{F}_a={}^o\mathbf{F}_{b1}+{}^o\mathbf{F}_{b2} \tag{3}$$

$$ {}^o\mathbf{N}_a={}^o\mathbf{N}_{b1}+{}^o\mathbf{N}_{b2}. \tag{4}$$

${}^{O}\mathbf{F}_a$ and ${}^{O}\mathbf{N}_a$ are the external force and moment on the object, respectively. By introducing the generalized force/moment vectors:

$$ {}^{O}\mathbf{f}_a=[{}^{O}\mathbf{F}_a^T\ {}^{O}\mathbf{N}_a^T]^T \tag{5} $$

$$ {}^{O}\mathbf{q}_b=[{}^{O}\mathbf{F}_{b1}^T\ {}^{O}\mathbf{N}_{b1}^T\ {}^{O}\mathbf{F}_{b2}^T\ {}^{O}\mathbf{N}_{b2}^T]^T. \tag{6} $$

(3) and (4) are written as follows:

$$ {}^{O}\mathbf{f}_a=\mathbf{W}{}^{O}\mathbf{q}_b \tag{7} $$

where

$$ \mathbf{W}=[\mathbf{I}_6\ \mathbf{I}_6] \tag{8} $$

where $\mathbf{I}_n$ (here n=6) represents the n×n unit matrix. It should be noted that the simplicity of $\mathbf{W}$ comes from the using of the virtual sticks: we can make $\mathbf{W}$ simple as such only after noting the forces and moments at the point O_a.

The matrix $\mathbf{W}$ maps the 12-dimensional vector ${}^{O}\mathbf{q}_b$ into the 6-dimensional vector ${}^{O}\mathbf{f}_a$. The rank of $\mathbf{W}$ is 6; therefore, the vector space of ${}^{O}\mathbf{f}_a$ which is the range of $\mathbf{W}$, is 6-dimensional and the null space of $\mathbf{W}$ is also 6-dimensional. The vector ${}^{O}\mathbf{q}_b$ belonging to this null space produces the internal force and moment on the object [15].

Since the null space is 6-dimensional we can make a 6-dimensional vector space corresponding to the null space by choosing as the bases a proper set of 6 orthogonally independent vectors from the null space. We define a 6-dimensional vector ${}^{O}\mathbf{f}_r$ belonging to this 6-dimensional vector space as an internal force/moment vector. Let us denote the matrix consisting of this set of 6 base vectors as $\mathbf{V}$. The vector ${}^{O}\mathbf{q}_b$ belonging to the null space which we denote ${}^{O}\mathbf{q}_r$ is given by

$$ {}^{O}\mathbf{q}_r=\mathbf{V}{}^{O}\mathbf{f}_r. \tag{9} $$

We choose $\mathbf{V}$ as

$$ \mathbf{V}=[\mathbf{I}_6\ -\mathbf{I}_6]^T, \tag{10} $$

and write ${}^{O}\mathbf{f}_r$ as

$$ {}^{O}\mathbf{f}_r=[{}^{O}\mathbf{F}_r^T\ {}^{O}\mathbf{N}_r^T]^T. \tag{11} $$

Hence we have

$$ {}^{O}\mathbf{q}_r=[{}^{O}\mathbf{F}_r^T\ {}^{O}\mathbf{N}_r^T\ -{}^{O}\mathbf{F}_r^T\ -{}^{O}\mathbf{N}_r^T]^T, \tag{12} $$

meaning that the internal force/moment vector ${}^{O}\mathbf{f}_r$ represents the forces and moments consisting of the force and moment ${}^{O}\mathbf{F}_r$ and ${}^{O}\mathbf{N}_r$ at O_a exerted by the stick 1 and the force and moment $-{}^{O}\mathbf{F}_r$ and $-{}^{O}\mathbf{N}_r$ in the opposite direction at O_a exerted by the stick 2.

The general solution of (7) for ${}^{O}\mathbf{q}_b$ when ${}^{O}\mathbf{f}_a$ is given is

$$ {}^{O}\mathbf{q}_b=\mathbf{W}^{+}{}^{O}\mathbf{f}_a+(\mathbf{I}_{12}-\mathbf{W}^{+}\mathbf{W})\mathbf{b} \tag{13} $$

where $\mathbf{W}^+$ is the Moore-Penrose inverse of $\mathbf{W}$ and $\mathbf{b}$ is an arbitrary 12-dimensional vector. Since the second term of (13) represents the null space of $\mathbf{W}$, (13) can be written as

$$ {}^{O}\mathbf{q}_b=\mathbf{W}^{+}{}^{O}\mathbf{f}_a+\mathbf{V}{}^{O}\mathbf{f}_r. \tag{14} $$

Therefore, defining the workspace force/moment vector ${}^{O}\mathbf{h}$ by combining the external force/moment vector ${}^{O}\mathbf{f}_a$ and the internal force/moment vector ${}^{O}\mathbf{f}_r$ as

$$ {}^{O}\mathbf{h}=[{}^{O}\mathbf{f}_a^T\ {}^{O}\mathbf{f}_r^T]^T \tag{15} $$

yields

$$ {}^{O}\mathbf{q}_b=\mathbf{U}{}^{O}\mathbf{h} \tag{16} $$

where

$$ \mathbf{U}=[\mathbf{W}^{+}\ \mathbf{V}]. \tag{17} $$

${}^{O}\mathbf{h}$ for ${}^{O}\mathbf{q}_b$ given is calculated by

$$ {}^{O}\mathbf{h}=\mathbf{U}^{-1}{}^{O}\mathbf{q}_b. \tag{18} $$

Therefore, we obtain

$$ {}^{O}\mathbf{f}_a={}^{O}\mathbf{f}_{b1}+{}^{O}\mathbf{f}_{b2} \tag{19} $$

$$ {}^{O}\mathbf{f}_r=1/2({}^{O}\mathbf{f}_{b1}-{}^{O}\mathbf{f}_{b2}). \tag{20} $$

2.2 Workspace Velocity Vectors

In order to express the motion of the tip of the virtual stick, we define the frame Σ_{bi} at the tip of the virtual stick as shown in Figure 3. Σ_{bi} is fixed to the tip of the virtual stick i and coincides with the object frame Σ_a at the beginning of motion. Let us denote the translational and rotational velocities of Σ_{bi} relative to Σ_o as ${}^{O}\mathbf{v}_{bi}$ and ${}^{O}\boldsymbol{\omega}_{bi}$, respectively. The generalized velocity vector at the tips of the two sticks which

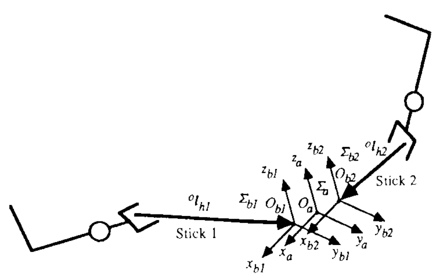


Figure 3: Virtual sticks and their tip frames

corresponds to the generalized force/moment vector ${}^{o}\mathbf{q}_b$, is defined as

$$ {}^{o}\mathbf{w}_b=[{}^{o}\mathbf{s}_{b1}{}^{T}\ {}^{o}\mathbf{s}_{b2}{}^{T}]^{T} \tag{21} $$

where

$$ {}^{o}\mathbf{s}_{bi}=[{}^{o}\mathbf{v}_{bi}{}^{T}\ {}^{o}\boldsymbol{\omega}_{bi}{}^{T}]^{T}. \tag{22} $$

Let us denote the workspace velocity vectors corresponding to ${}^{o}\mathbf{f}_a$ and ${}^{o}\mathbf{f}_r$ as ${}^{o}\mathbf{s}_a$ and ${}^{o}\Delta\mathbf{s}_r$, respectively, and define the workspace velocity vector ${}^{o}\mathbf{u}$ corresponding to the worksapce force/moment vector ${}^{o}\mathbf{h}$ as

$$ {}^{o}\mathbf{u}=[{}^{o}\mathbf{s}_a{}^{T}\ {}^{o}\Delta\mathbf{s}_r{}^{T}]^{T}. \tag{23} $$

If we suppose that ${}^{o}\mathbf{q}_b$ and ${}^{o}\mathbf{h}$ are balanced and if we think about the virtual work done by ${}^{o}\mathbf{q}_b$ and ${}^{o}\mathbf{h}$, we obtain

$$ {}^{o}\mathbf{u}=\mathbf{U}^{T\,o}\mathbf{w}_b. \tag{24} $$

This means that

$$ {}^{o}\mathbf{s}_a=1/2({}^{o}\mathbf{s}_{b1}+{}^{o}\mathbf{s}_{b2}) \tag{25} $$

$$ {}^{o}\Delta\mathbf{s}_r={}^{o}\mathbf{s}_{b1}-{}^{o}\mathbf{s}_{b2}. \tag{26} $$

We designate that ${}^{o}\mathbf{s}_a$ represents the translational and rotational velocities of the object. ${}^{o}\Delta\mathbf{s}_r$ represents the relative translational and rotational velocities between the frames Σ_{b1} and Σ_{b2} if O_{b1} and O_{b2} coincide. Since we assume that the relative position and orientation between Σ_{b1} and Σ_{b2} are very small, we can regard ${}^{o}\Delta\mathbf{s}_r$ as the relative translational and rotational velocities of Σ_{b1} to Σ_{b2}.

2.3 Workspace Position Vectors

We define the position/orientation vectors of the frames Σ_{bi} and Σ_a relative to the base frame Σ_o as follows:

$$ {}^{o}\mathbf{p}_{bi}=[{}^{o}\mathbf{x}_{bi}{}^{T}\ {}^{o}\boldsymbol{\phi}_{bi}{}^{T}]^{T} \tag{27} $$

$$ {}^{o}\mathbf{p}_a=[{}^{o}\mathbf{x}_a{}^{T}\ {}^{o}\boldsymbol{\phi}_a{}^{T}]^{T} \tag{28} $$

where ${}^{o}\mathbf{x}_{bi}$ and ${}^{o}\mathbf{x}_a$ are the position vectors from the origin of Σ_o to the origins of Σ_{bi} and Σ_a, respectively, and ${}^{o}\boldsymbol{\phi}_{bi}$ and ${}^{o}\boldsymbol{\phi}_a$ are the orientation vectors of Σ_{bi} and Σ_a to Σ_o, respectively.

Generally, the integration of the velocity vectors ${}^{o}\mathbf{s}_{bi}$ and ${}^{o}\mathbf{s}_a$ does not give the position/orientation vectors ${}^{o}\mathbf{p}_{bi}$ and ${}^{o}\mathbf{p}_a$, respectively, because the integration of the rotational velocity of an object does not give a unique representation of its orientation. ${}^{o}\mathbf{s}_{bi}$ and ${}^{o}\mathbf{s}_a$, however, can be calculated from the derivatives of ${}^{o}\mathbf{p}_{bi}$ and ${}^{o}\mathbf{p}_a$, respectively, as

$$ {}^{o}\mathbf{s}_{bi}=\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{bi}){}^{o}\dot{\mathbf{p}}_{bi} \tag{29} $$

$$ {}^{o}\mathbf{s}_a=\mathbf{B}_s({}^{o}\boldsymbol{\phi}_a){}^{o}\dot{\mathbf{p}}_a. \tag{30} $$

$\mathbf{B}_s(\cdot)$ is a 6×6 matrix function of the orientation vector ${}^{o}\boldsymbol{\phi}_{bi}$ or ${}^{o}\boldsymbol{\phi}_a$, and transforms the time derivative of the orientation vector of a frame into its rotational velocity.

Using the relations (29) and (30), we define workspace position vectors.

Substituting (29) and (30) into (25) yields

$$ \mathbf{B}_s({}^{o}\boldsymbol{\phi}_a){}^{o}\dot{\mathbf{p}}_a=1/2\{\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{b1}){}^{o}\dot{\mathbf{p}}_{b1}+\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{b2}){}^{o}\dot{\mathbf{p}}_{b2}\}. \tag{31} $$

Since we have assumed that the Σ_{b1}, Σ_{b2} and Σ_a are very close, we can suppose that

$$ \mathbf{B}_s({}^{o}\boldsymbol{\phi}_a)\simeq\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{b1})\simeq\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{b2}). \tag{32} $$

Therefore, if we assume that the initial values of ${}^{o}\mathbf{p}_a$, ${}^{o}\mathbf{p}_{b1}$ and ${}^{o}\mathbf{p}_{b2}$ are all equal, the integration of (31) gives

$$ {}^{o}\mathbf{p}_a=1/2({}^{o}\mathbf{p}_{b1}+{}^{o}\mathbf{p}_{b2}). \tag{33} $$

We define the relative position/orientation vector ${}^{o}\Delta\mathbf{p}_r$ of Σ_{b1} to Σ_{b2} so that

$$ {}^{o}\Delta\mathbf{s}_r=\mathbf{B}_s({}^{o}\boldsymbol{\phi}_a){}^{o}\Delta\dot{\mathbf{p}}_r. \tag{34} $$

Substituting (29) and (34) into (26) yields

$$ \mathbf{B}_s({}^{o}\boldsymbol{\phi}_a){}^{o}\Delta\dot{\mathbf{p}}_r=\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{b1}){}^{o}\dot{\mathbf{p}}_{b1}-\mathbf{B}_s({}^{o}\boldsymbol{\phi}_{b2}){}^{o}\dot{\mathbf{p}}_{b2}. \tag{35} $$

Therefoe, if we assume again that the initial values of ${}^{o}\mathbf{p}_{b1}$ and ${}^{o}\mathbf{p}_{b2}$ are equal and that that of ${}^{o}\Delta\mathbf{p}_r$ is zero, the integration of (35) gives

$$ {}^{o}\Delta\mathbf{p}_r={}^{o}\mathbf{p}_{b1}-{}^{o}\mathbf{p}_{b2}. \tag{36} $$

We define the workspace position/orientation vector ${}^{o}\mathbf{z}$ by combining the position/orientation vector ${}^{o}\mathbf{p}_a$ of Σ_a and the relative position/orientation vector ${}^{o}\Delta\mathbf{p}_r$ of Σ_{b1} to Σ_{b2} as

$$ {}^{o}\mathbf{z}=[{}^{o}\mathbf{p}_a{}^{T}\ {}^{o}\Delta\mathbf{p}_r{}^{T}]^{T}, \tag{37} $$

and the generalized position/orientation vector ${}^{o}\mathbf{y}_b$ as

$$ {}^{o}\mathbf{y}_b=[{}^{o}\mathbf{p}_{b1}{}^{T}\ {}^{o}\mathbf{p}_{b2}{}^{T}]^{T}. \tag{38} $$

From (17), (33) and (36), ${}^{o}\mathbf{z}$ is calculated from ${}^{o}\mathbf{y}_b$ by

$$ {}^{o}\mathbf{z}=\mathbf{U}^{T\,o}\mathbf{y}_b. \tag{39} $$

2.4 Representation of Internal Workspace Vectors

We have derived the workspace force vector ${}^o\mathbf{h}$ given by (15), the workspace velocity vector ${}^o\mathbf{u}$ given by (23) and the workspace position vector ${}^o\mathbf{z}$ given by (37). However, there is a problem in using these vectors to implement the symmetric non-master/slave coordinated control scheme. The problem is that the bottom half components, ${}^o\mathbf{f}_r$, ${}^o\Delta\mathbf{s}_r$ and ${}^o\Delta\mathbf{p}_r$ of these vectors, are expressed with respect to the base frame Σ_o. Therefore, it is difficult to describe tasks such as pushing or twisting of an object. In order to specify pushing or twisting force or moment, it is necessary to represent the internal force or moment with respect to the object frame Σ_a.

Let us denote the 3×3 matrix transforming a vector from Σ_o to Σ_a as ${}^a\mathbf{A}_o$, which is a function of the orientation vector ${}^o\boldsymbol{\phi}_a$ of Σ_a:

$$ {}^a\mathbf{A}_o = {}^a\mathbf{A}_o({}^o\boldsymbol{\phi}_a). \tag{40} $$

By using ${}^a\mathbf{A}_o$, we make a 6×6 transformation matrix

$$ {}^a\mathbf{R}_o = \mathrm{diag}[{}^a\mathbf{A}_o \; {}^a\mathbf{A}_o] \tag{41} $$

which transforms the internal force/moment vector ${}^o\mathbf{f}_r$ with respect to Σ_o into ${}^a\mathbf{f}_r$ with respect to Σ_a, and the relative translational/rotational velocity vector ${}^o\Delta\mathbf{s}_r$ with respect to Σ_o into ${}^a\Delta\mathbf{s}_r$ with respect to Σ_a, as

$$ {}^a\mathbf{f}_r = {}^a\mathbf{R}_o {}^o\mathbf{f}_r \tag{42} $$

$$ {}^a\Delta\mathbf{s}_r = {}^a\mathbf{R}_o {}^o\Delta\mathbf{s}_r. \tag{43} $$

The orientation component ${}^o\Delta\boldsymbol{\phi}_r$ of ${}^o\Delta\mathbf{p}_r$ is not a real vector, but only a set of three parameters. Therefore, we cannnot calculate ${}^a\Delta\boldsymbol{\phi}_r$ directly by ${}^a\Delta\boldsymbol{\phi}_r = {}^a\mathbf{A}_o {}^o\Delta\boldsymbol{\phi}_r$. However, since ${}^o\Delta\mathbf{p}_r$ is small, we can transform its orientation component ${}^o\Delta\boldsymbol{\phi}_r$ into a rotation vector ${}^o\Delta\boldsymbol{\Omega}_r$ by using $\mathbf{B}_s({}^o\boldsymbol{\phi}_a)$ defined by (30), as

$$ \mathbf{B}_s({}^o\boldsymbol{\phi}_a){}^o\Delta\mathbf{p}_r = [{}^o\Delta\mathbf{x}_r^T \; {}^o\Delta\boldsymbol{\Omega}_r^T]^T. \tag{44} $$

The vector $\mathbf{B}_s({}^o\boldsymbol{\phi}_a){}^o\Delta\mathbf{p}_r$ with respect to Σ_o is transformed into ${}^a\Delta\mathbf{p}_r$ with respect to Σ_a by ${}^a\mathbf{R}_o$, as

$$ {}^a\Delta\mathbf{p}_r = {}^a\mathbf{R}_o({}^o\boldsymbol{\phi}_a)\mathbf{B}_s({}^o\boldsymbol{\phi}_a){}^o\Delta\mathbf{p}_r. \tag{45} $$

Now we have transformed all the internal workspace vectors. A prime concern in these transformation is if the derivative of the new workspace relative position/orientation vector ${}^a\Delta\mathbf{p}_r$ gives the new workspace relative velocity vector ${}^a\Delta\mathbf{s}_r$. This is checked as follows: Since we have assumed that Σ_{b1} and Σ_{b2} are very close, namely ${}^o\Delta\mathbf{p}_r \simeq \mathbf{0}$, we obtain

$$ {}^a\Delta\dot{\mathbf{p}}_r \simeq {}^a\mathbf{R}_o({}^o\boldsymbol{\phi}_a)\mathbf{B}_s({}^o\boldsymbol{\phi}_a){}^o\Delta\dot{\mathbf{p}}_r = {}^a\Delta\mathbf{s}_r \tag{46} $$

It is noted that the duality relationship between the workspace relative velocity vector ${}^a\Delta\mathbf{s}_r$ and the workspace internal force/moment vector ${}^a\mathbf{f}_r$, still holds.

By using these internal workspace vectors ${}^a\mathbf{f}_r$, ${}^a\Delta\mathbf{s}_r$ and ${}^a\Delta\mathbf{p}_r$, we can describe manipulation of an object done by two robots, such as twisting, bending, pushing, pulling, or shearing of an object. In Figure 4, we illustrate these cases of manipulation with representing them by using the components of ${}^a\mathbf{f}_r$ defined by

$$ {}^a\mathbf{f}_r = [{}^aF_{xr} \; {}^aF_{yr} \; {}^aF_{zr} \; {}^aN_{xr} \; {}^aN_{yr} \; {}^aN_{zr}]^T. \tag{47} $$

The components of ${}^a\Delta\mathbf{p}_r$ represent the 6-dimensional deformation of the object if we assume that there is no slippage of the hands on the object. By using these parameters as well as the components of ${}^a\mathbf{f}_r$, we can control the deformation of the object.

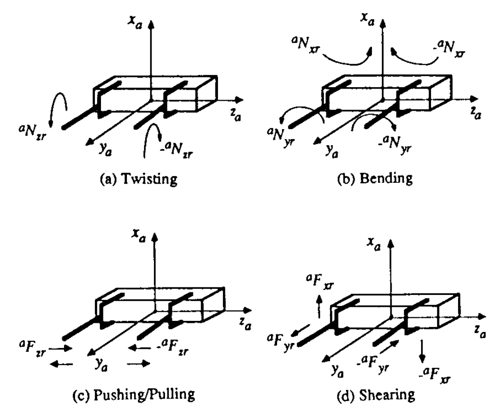


Figure 4: Description of coordinated tasks

3. Symmetric Coordinated Control Scheme

3.1 Organization of the Control Scheme

The organization of the coordinated position/force control scheme using the workspace vectors derived in Section 2, is shown diagramatically in Figure 5, which looks like the hybrid scheme proposed for a single arm robot [16] except that the workspace vectors are those of a unique workspace shared by the two robots. This control scheme is simple. We owe this simplicity to the consistent definition of the workspace force, velocity and position vectors presented in this paper.

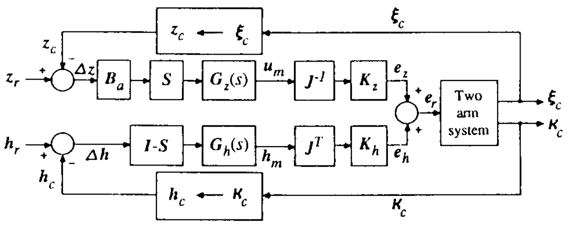


Figure 5: A block diagram of the coordinated position/force control scheme

$\mathbf{z}$, $\mathbf{u}$ and $\mathbf{h}$ in the figure are the generalized position, velocity and force vectors in the workspace, respectively, defined by

$$\mathbf{z}=[{}^{o}\mathbf{p}_a{}^T \; {}^{a}\Delta\mathbf{p}_r{}^T]^T \tag{48}$$

$$\mathbf{u}=[{}^{o}\mathbf{s}_a{}^T \; {}^{o}\Delta\mathbf{s}_r{}^T]^T \tag{49}$$

$$\mathbf{h}=[{}^{o}\mathbf{f}_a{}^T \; {}^{a}\mathbf{f}_r{}^T]^T. \tag{50}$$

The vector $\boldsymbol{\xi}$ is a jointspace vector representing the displacements of the joints of the two robots. The vector $\boldsymbol{\kappa}$ is a force/moment vector representing the forces and moments measured by the force sensors at the wrists of the robots. The suffixes r, c and m in the figure represent reference values, current values and feedback commands in the workspace, respectively.

The command vector $\mathbf{e}_r$ to the motors driving the two robots is calculated by

$$\mathbf{e}_r=\mathbf{e}_z+\mathbf{e}_h \tag{51}$$

where $\mathbf{e}_z$ is the command vector in the jointspace to correct position/orientation error in the workspace, and is calculated by

$$\mathbf{e}_z=\mathbf{K}_z\mathbf{J}^{-1}\mathbf{G}_z(s)\mathbf{S}\mathbf{B}_a({}^{o}\boldsymbol{\phi}_a)(\mathbf{z}_r-\mathbf{z}_c) \tag{52}$$

and $\mathbf{e}_h$ is the command vector in the jointspace to correct force/moment error in the workspace, and is calculated by

$$\mathbf{e}_h=\mathbf{K}_h\mathbf{J}^T\mathbf{G}_h(s)(\mathbf{I}-\mathbf{S})(\mathbf{h}_r-\mathbf{h}_c) \tag{53}$$

where $\mathbf{B}_a({}^{o}\boldsymbol{\phi}_a)$ is a 12×12 matrix function of ${}^{o}\boldsymbol{\phi}_a$ transforming errors in the rotation angles of Σ_a into a rotation vector, and is given by

$$\mathbf{B}_a({}^{o}\boldsymbol{\phi}_a)=\mathrm{diag}[\mathbf{B}_s({}^{o}\boldsymbol{\phi}_a) \;\; \mathbf{I}_6]. \tag{54}$$

$\mathbf{J}$ is the Jacobian matrix of the nonlinear transformation from the jointsapce vector $\boldsymbol{\xi}$ to the worksapce vector $\mathbf{z}$. $\mathbf{J}$ is calculated as a function of the Jacobian matrices of each robot using the relations (21)-(24), (43) and (49) in Sections 2 and 3.

$\mathbf{G}_z(s)$ and $\mathbf{G}_h(s)$ are operators representing control laws of position and force in the workspace, respectively. $\mathbf{K}_z$ and $\mathbf{K}_h$ are diagonal matrices of which diagonal elements convert velocity and force commands in the jointspace, respectively, into motor commands.

$\mathbf{S}$ is a matrix to select control modes between position control mode and force control mode. Usually, $\mathbf{S}$ is diagonal and its diagonal elements are 1 or 0 crresponding to position control mode or force control mode, respectively. $\mathbf{I}$ is the unit matrix with the same dimension as $\mathbf{S}$.

3.2 Coordinate Transformations Needed

In order to implement the control scheme, we need equations for calculating the feedback vectors $\mathbf{z}_c$ and $\mathbf{h}_c$, and the command vector $\mathbf{e}_r$. The transformation required for such calculations are: those from the jointspace position vector $\boldsymbol{\xi}_c$ to the workspace position/orientation vector $\mathbf{z}_c$; from the force/moment vector $\boldsymbol{\kappa}_c$ measured by the force sensors to the workspace force/moment vector $\mathbf{h}_c$; from the feedback velocity command vector in the workspace $\mathbf{u}_m$ to the velocity command vector in the jointspace; and from the feedback force/moment command vector in the workspace $\mathbf{h}_m$ to the force/torque command vector in the jointspace. The transformation from $\mathbf{u}_m$ to the jointspace velocity and from $\mathbf{h}_m$ to the jointspace force/torque can be achieved by using the Jacobian matrix $\mathbf{J}$ of the transformation from $\boldsymbol{\xi}$ to $\mathbf{z}$.

Therefore, the equations we have to derive to implement the control scheme are those for the direct kinematics transforming $\boldsymbol{\xi}$ to $\mathbf{z}$, the differential kinematics calculating the Jacobian matrix $\mathbf{J}$, and the calculation of $\mathbf{h}$ from $\boldsymbol{\kappa}$. By using direct kinematic equations for a single arm, the positons and orientations of the frames Σ_{b1} and Σ_{b2} at the tips of the virtual sticks are easily calculated. Substituting these values into (37)-(39), (45) and (48) yields $\mathbf{z}$. The forces and moments at the tips of the virtual sticks are also easily calculated from the measurement of the vector $\boldsymbol{\kappa}$. Substituting these values into (15), (17), (18), (42) and (50) yields $\mathbf{h}$. The Jacobian matrix $\mathbf{J}$ is calculated from the Jacobian matrices of each arm by referring (21)-(24), (43) and (49).

4. Concluding Remarks

The task consisting of manipulating an object with two cooperating robots has been studied. We have proposed a solution based upon a non-master/slave position/force control scheme. The theory presented in this paper complements the experiment done by Uchiyama et al. [11].

The control scheme allows the two robots to carry an object safely, either by grasping, pulling, or pushing it. The two robots playing similar roles, all the workspace vectors include information about both the robots, which can then be considered as a single coupled mechanism. This feature of the method, along with both an absolute and a relative description of the task, allow the implementation of a quite simple coordinated control scheme, which looks like the hybrid control scheme used for a single arm robot.

However, the difficulty is to ensure the consistency of the various workspace vectors, namely position, velocity, and force vectors. To ensure this consistency, we first analyzed the statics of the system, and, introducing the concept of a virtual stick, defined a workspace force vector including external and internal forces and moments. Then, using the duality relation between force and velocity in mechanics, we derived a workspace velocity vector including the absolute velocity of the object and the relative velocity between the tips of the virtual sticks.

The calculation of the workspace position vector by integrating the workspace velocity vector could seem straightforward; however, the direct integration of the rotational components of the velocity vector gives no unique representation of the orientation components of the position vector. Therefore, at that point, we had to assume explicitly that the deformation of the object was very small, in order to proceed with our calculation. The assumption limits the application field of our equations.

A suggestion for future work can be to extend the theory to the case of large relative motion of the hands, such as the using of scissors, or assembly tasks with one object in each hand. On a practical point of view, the implementation of the proposed method requires the calculation and the manipulation of many variables in real time; therefore an effort has to be directed to developing a controller having fast computational means such as DSP's or dedicated VLSI's.

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References

[1] H. Kikuchi, T. Niinomi, M. Sato, and Y. Matsumoto, "Heavy Parts Assembly by Coordinative Control of Robot and Balancing Manipulator", in Proc. IFAC 9th World Congress, Budapest, vol. VI, pp. 175-180, July 1984.

[2] R. Zapata, P. Dauchez, and P. Coiffet, "Cooperation of Robots in Gripping Tasks: the Exchange Problem", Robotica, vol. 1, no. 2, pp. 73-77, 1983.

[3] Y. F. Zheng and J. Y. S. Luh, "Joint Torques for Control of Two Coordinated Moving Robots", in Proc. 1986 IEEE Int. Conf. on Robotics and Automation, San Francisco, pp. 1375-1380, April 1986.

[4] T. J. Tarn, A. K. Bejczy, and X. Yun, "Design of Dynamic Control of Two Cooperating Robot Arms: Closed Chain Formulation", in Proc. 1987 IEEE Int. Conf. on Robotics and Automation, Raleigh, pp. 7-13, March 1987.

[5] P. Dauchez and R. Zapata, "Co-ordinated Control of Two Cooperative Manipulators: the Use of a Kinematic Model", in Proc. 15th Int. Symp. Industrial Robots, Tokyo, pp. 641-648, September 1985.

[6] M. Kohno, A. Miyakawa, and M. Hosoya, "Real Time Synchronization of Two Robots for Coordinated Assembly", in Proc. 16th Int. Symp. Industrial Robots, Brussels, pp. 219-228, September 1986.

[7] E. Freund, "Hierarchical Nonlinear Control for Robots", in Robotics Research - First International Symposium, Cambridge, MA: the MIT Press, pp. 817-840, 1984.

[8] E. Nakano, S. Ozaki, T. Ishida, and I. Kato, "Cooperational Control of the Anthropomorphous Manipulator 'MELARM' ", in Proc. 4th Int. Symp. Industrial Robots, Tokyo, pp. 251-260, November 1974.

[9] S. Fujii and S. Kurono, "Coordinated Computer Control of a Pair of Manipulators", in Proc. 4th IFToMM World Congress, University of Newcastle upon Tyne, England, pp. 411-417, September 1975.

[10] S. Hayati, "Hybrid Position/Force Control of Multi-Arm Cooperating Robots", in Proc. 1986 IEEE Int. Conf. on Robotics and Automation, San Francisco, pp. 82-89, April 1986.

[11] M. Uchiyama, N. Iwasawa, and K. Hakomori, "Hybrid Position/Force Control for Coordination of a Two-Arm Robot", in Proc. 1987 IEEE Int. Conf. on Robotics and Automation, Raleigh, pp. 1242-1247, March 1987.

[12] P. Dauchez and M. Uchiyama, "Kinematic Formulation for Two Force Controlled Cooperating Robots", in Proc. '87 Int. Conf. Advanced Robotics, Versailles, pp. 457-467, October 1987.

[13] M. Uchiyama and P. Dauchez, "Statics, Kinematics, and Hybrid Control Scheme for a Two Arm Robot", in Proc. 9th IASTED Int. Symp. Robotics and Automation, Santa Barbara, California, pp. 28-32, May 1987.

[14] M. T. Mason, "Compliance and Force Control for Computer Controlled Manipulators", IEEE Trans. on Systems, Man and Cybernetics, vol. SMC-11, no. 6, pp. 418-432, 1981.

[15] Y. Nakamura, K. Nagai, and T. Yoshikawa, "Mechanics of Coordinative Manipulation by Multiple Robotic Mechanisms", in Proc. 1987 IEEE Int. Conf. on Robotics and Automation, Raleigh, pp. 991-998, March 1987.

[16] M. H. Raibert and J. J. Craig, "Hybrid Position/Force Control of Manipulators", Trans. ASME, J. of Dynamic Systems, Measurement, and Control, vol. 103, no. 2, pp. 126-133, 1981.