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UNKNOWN LOAD DISTRIBUTION OF TWO INDUSTRIAL ROBOTS

Kab Il Kim
Dept. of Electrical Engineering
Myung Ji University
Seoul, Korea

Yuan F. Zheng
Dept. of Electrical Engineering
The Ohio State University
Columbus, OH 43210

Abstract

Unknown load distribution between two coordinated industrial robots are studied in this paper. Two methods are proposed for the distribution. The first method is called *load estimation* method, in which the parameters associated with the load are estimated using the information of two wrist force sensors. As a result, the load becomes known. Conventional methods can then be applied to distribute the force. The second method is called the *force compensation* method in which one of the robots called the leader takes the major role of carrying the load. The load is compensated by another robot called follower until the leader can carry the load to follow a satisfactory trajectory.

1. Introduction

Load distribution problem was previous studied by a number of papers for multiple manipulators [1-5] and multi-finger hands [6-9]. In general, the studies address the problem of how a load should be optimally distributed among multiple robots or multiple fingers such that certain criterion can be met. For example, Orin and Oh [4] have studied the control of force distribution for closed-chain robotic mechanisms. A weighted combination of energy consumption and load balancing was selected as a criterion. The linear programming technique was used to obtain a solution. More recently, Zheng and Luh [1] proposed several distribution methods for two coordinated manipulators using a number of criteria, including the least energy consumption, the minimum force exertion on the end-effectors, etc.

Unfortunately, in most of the previous studies, the load to the systems, including mass and inertias, was assumed known. In reality, however, when a robotic system works in an unstructured environment, the load is often unknown. Unknown load distribution is an under-studied problem, especially for multiple robot system. This problem is to be studied in this paper.

We propose two methods for load distribution among the two industrial robots. The first method is called load estimation, and the second method is called force compensation. In the load estimation method, the load is first estimated by using two wrist force sensors installed on each robots. Once the load is estimated, all the distribution methods previously developed in other works can be then be used. Reviewing of the previous research revealed that load estimation was previously studied for a single arm [10]. Our method will merely be an extension of the methods developed for a single manipulators.

The force compensation method is a completely new approach. In this approach, one of the robots called leader takes the major responsibility of carrying the load. Only when the load can not be sustained by the leader, the other robot called follower will assist. Since the load does not need to be estimated before the load starts to be carried, the second method is more responsive and computationally efficient than the first method.

The structure of the paper is as follows. In the next section, load estimation by two industrial robots is first studied. In the third section, our study is concentrated on the force compensation method. Simulation results for the force compensation method are presented in the fourth section which is followed by the section of Conclusions.

2. The Load Estimation Method

Load estimation was previously studied for a single robot arm [10], in which a wrist force sensor was used to estimate the force. In our study, the estimation method of [10] is extended to two arms holding one rigid object. In this case, two wrist force sensors are needed for the estimation of the load.

For convenience purpose, one of the robots, robot 1 is named the leader, and the other robot, robot 2, the follower. We first derive the Newton-Euler equations for the two robots holding a rigid object (Fig. 1). From Fig. 1, it can be seen that the Newton equation of the load is

$$f_1 - f_2 + m_c g - m_c \ddot{x}_c = 0 \qquad (1)$$

where

f_1: force exerted at the leader end-effector,
f_2: force exerted at the follower end-effector,
m_c: mass of the load,

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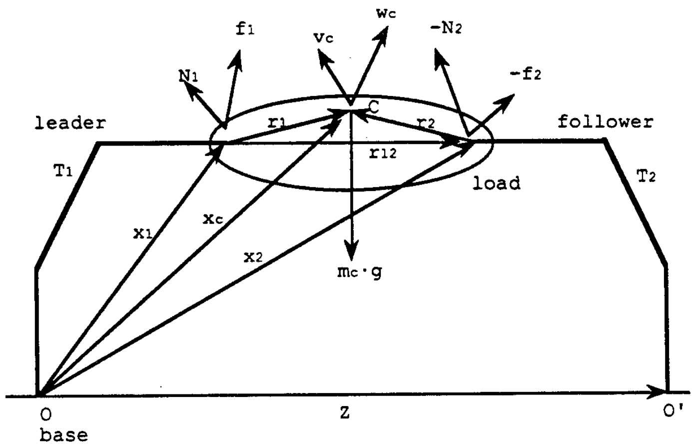

Fig. 1 Two robots hold an object and the associated parameters

x_c: acceleration at the centroid of the load,
c: mass center (centroid) of the load and
g: gravitational acceleration.

Also from Fig. 1, the Euler equation of the load is

$$N_1 - N_2 - (r_{12}+r_2)\underline{x}f_1 + r_2\underline{x}f_2 - I_c\dot{w}_c - w_c\underline{x}(I_c w_c) = 0 \quad (2)$$

where

N_1 and N_2 are the moments of the leader and follower end effectors, respectively,
r_{12}, r_2 are the position vector from leader to follower and follower to centroid, respectively,
I_c is the centroidal inertia tensor of load,
w_c, w_c are the rotational velocity and the acceleration of the load, respectively and
$\underline{x}$ is the vector product.

As for the kinematic behavior, the following transformation relation can be obtained from Fig 1:

$$X = (T_1)^{-1} Z\, T_2 \quad (3)$$

where

T_1, T_2 and 4x4 homogeneous transformation matrices from the base to the end-effectors of the leader and follower, respectively,
Z is the transformation from the base of the leader to the base of the follower (4x4 matrix) and
X is the transformation from the end-effector of the leader to the end-effector of the follower (4x4 matrix).

Let the rotational matrix (3x3) of X be R, and the position vector (3x1) of X be P. Then, P is the same as r_{12} in Fig 1, i.e.,

$$X = \begin{vmatrix} R & P \\ 0 & 1 \end{vmatrix}, \quad (4)$$

where $P = [P_x\, P_y\, P_z]^T = r_{12}$. Let the rotation part of T_1 be R_1, and the position part be P_1, namely

$$T_1 = \begin{vmatrix} R_1 & P_1 \\ 0 & 1 \end{vmatrix}, \quad (5)$$

Then, we may have

$$R_1 r_{12} = x_1 - x_2 \quad (6)$$

where
x_1, x_2 are position vectors from the base to the end-effector of the leader and follower, respectively. Let f and N be

$$f = f_1 - f_2 \text{ and} \quad (7)$$

$$N = N_1 - N_2 - r_{12}\underline{x}f_1. \quad (8)$$

Replacing f_1, f_2, N_1, and N_2 in (1) and (2) by (7) and (8), one obtains

$$f = -m_c g + m_c\ddot{x}_c \text{ and} \quad (9)$$

$$N = r_2 x f_1 - r_2\underline{x}f_2 + I_c\dot{w}_c + w_c\underline{x}(I_c w_c)$$
$$= r_2\underline{x}f + I_c\dot{w}_c + w_c\underline{x}(I_c w_c) \quad (10)$$

Meanwhile, from Fig 1, one has

$$x_c = x_2 + r_2, \tag{11}$$

and the first and second time derivatives of (11) are

$$\dot{x}_c = \dot{x}_2 + w_c \underline{x} r_{12} \text{ and} \tag{12}$$

$$\ddot{x}_c = \ddot{x}_2 + \dot{w}_c \underline{x} r_2 + w_c \underline{x}(w_c \underline{x} r_2). \tag{13}$$

Here, $\dot{w}_c \underline{x} r_2$ may be vanished, if the angular velocity of the rotation about fixed axes is constant.

By using (13), (9) becomes

$$f = m_c(-g+\ddot{x}_2)+\dot{w}_c \underline{x} m_c r_2 + w_c \underline{x}(w_c \underline{x} m_c r_2) \tag{14}$$

and using (14), (10) becomes

$$N = r_2 \underline{x} m_c(-g+\ddot{x}_2) + r_2 \underline{x}(\dot{w}_c \underline{x} m_c r_2) + r_2 \underline{x}[w_c \underline{x} (w_c \underline{x} m_c r_2)] + I_c \dot{w}_c + w_c \underline{x}(I_c w_c) \tag{15}$$

From the three dimensional version of the parallel axis theorem as cited in [11], one has

$$I_2 = I_c + m_c[(r_2^T r_2)I - (r_2 r_2^T)] \tag{16}$$

where

I: a 3x3 identity matrix and

I_2: inertia matrix with respect to the follower end-effector.

Using equation (16) and with some treatments, (15) becomes

$$N = (g-\ddot{x}_2)\underline{x} m_c r_2 + I_2 \dot{w}_c + w_c \underline{x}(I_2 w_c). \tag{17}$$

Combining (14) and (17), one can obtain

$$F_{ti} = W_i L_i \tag{18}$$

where

$F_{ti} = [f\ N]^T$, a 6x1 vector

$$W_i = \begin{vmatrix} \ddot{x}_2\text{-}g & [w_c\underline{x}]+[w_c\underline{x}][w_c\underline{x}] & 0 \\ 0 & [(g-\ddot{x}_2)\underline{x}] & [w_c']+[w_c\underline{x}][w_c'] \end{vmatrix}$$

and

$L_i = [m_c \quad m_c r_2 \quad I_2']^T$, a 10x1 vector

in which w_c' is a matrix, i.e.,

$$w_c' = \begin{vmatrix} w_x & w_y & w_z & 0 & 0 & 0 \\ 0 & w_x & 0 & w_y & w_z & 0 \\ 0 & 0 & w_x & 0 & w_y & w_z \end{vmatrix} \text{ and } I_2' \text{ is}$$

a vector, i.e.

$$I_2' = [I_{11}\ I_{12}\ I_{13}\ I_{22}\ I_{23}\ I_{33}]^T$$

In (18), there are 6 known variables (3 in f, and the other 3 in N), and 10 unknown variables. Consequently, we need at least two different manipulator configurations to solve the unknown variables (12 equations, 10 unknowns). However, in general, more data sets can make the estimation more precise. If n data sets are used (n>=2), the least-square estimation yields

$$W^T F_t = W^T W L_i \tag{19}$$

from which one has

$$L_i = (W^T W)^{-1} W^T F_t \tag{20}$$

where

$$W = [W_1\ W_2\ ..\ W_n]^T \text{ and } F_t = [F_{t1}\ \ F_{t2}\ ..\ F_{t3}]^T.$$

From equation (20), it can be seen that mass (m_c) and moment of inertia (I_2) as well as r_2 can be calculated as long as F_t is provided. Using r_2, r_1 can be further derived as

$$r_1 = r_{12} - r_2 \tag{21}$$

where

r_{12} was obtained by using (7).

Using I_2 and r_2, however, I_c can be estimated using (16). With the load being estimated, the unknown load distribution can be treated as a known load distribution problem. For a known load, many methods previously developed by other researchers [1-9] can be used which will not be further addressed here.

3. The Force Compensation Method

In the force compensation method, the load is not estimated. Instead, the leader takes the main role of carrying the load, and use the position control strategy to move the object following a pre-defined motion profile. Only when the trajectory of the object can not satisfy the pre-defined motion profile, the follower starts to help. In this regard, the motion errors of the object are transformed into required compensating force of the follower. Then the follower uses force control strategy to provide the compensation force. As a result, the position-force control strategy as developed in our previous work must be used [12]. In [12], it also has been proved that this kind of position-force control strategy is stable for two industrial robots carrying a single object. To apply the position-force control strategy, a wrist force sensor is required to installed on the follower [12].

When leader follows a given trajectory within admissible error bound, the follower just follows the leader without providing any force. When the leader is overburdened, the position error is beyond a certain threshold. This means that one or more of the joint torques of the leader are beyond the limit of their bound, i.e.,

$$|T_{1i}| > |T_{1imax}| \quad (22)$$

where

T_{1i}: i-th joint torque of the leader, and
T_{1imax}: the limit of T_{1i}.

In this case, the position error becomes

$$|x_1 - x_{1d}| = \mathbf{e} > \mathbf{d} \quad (23)$$

where

e: position error and
d: admissible position error bound.

In position control, there always exists position error in normal control, and this kind of position error is usually within the bound of **d**. However, when the load is too heavy, the position error **e** will be greater than the bound **d**. The problem is how to reduce the absolute value of the required torque at joint i. Unfortunately, the torque of the leader is not measured, because the leader uses position control. The only parameter can be used is the actual position of the joint. One possible way of reducing the leader torque is to reduce the load of the leader.

The overall control strategy of the system is as follows (Fig. 2). First, position error is changed to the torque value (ΔT_1) of the leader using

$$\Delta T_1 = J_1^T k_p \mathbf{e} \quad (24)$$

where

ΔT_1: required compensating torque,
J_1^T: transpose of leader Jacobian matrix and
k_p: position feedback gain.

Secondly, after the required compensating torque is determined, the compensating force of the leader can be calculated as

$$\Delta F_1 = (J_1^T)^{-1} \Delta T_1 \quad (25)$$

Thirdly, this compensating force (ΔF_1) should be provided by the follower. This means that the compensating force should be added to the follower force that is originally designed for the follower end-effector. From Fig. 2, it can be seen that

$$F_f = F_d - (F_c + \Delta F_1) \quad (26)$$

where

F_f: input force of the force controller,
F_d: desired force of the follower and
F_c: force measured by the sensor.

Here, $F_c + \Delta F_1$ is considered as the new follower reaction force. Since in reality, the force sensor is attached to the follower, $F_c = F_2$. Thus, the effect of the compensation is equivalent to change the follower reaction force as follows:

$$F_2' = F_2 + \Delta F_1 \quad (27)$$

Equation (27) gives the new follower force which needs to be provided to the object. The force also reflects the compensation effeort to the leader.

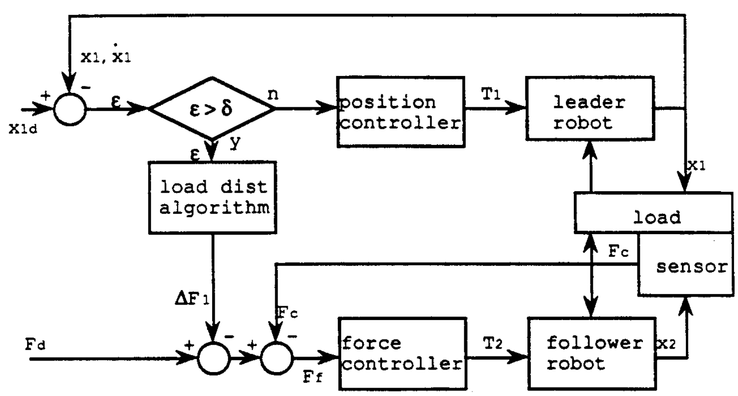

Fig. 2 Block diagram of the force compensation method

Fourthly, this changing of force is transferred to the leader without changing any configurations using direct force control [12]. That is, find how the change of the follower end-effector force affects the force exerted on the leader. After the compensation, the force at the leader becomes (Fig. 3)

$$F_1' = F_o - F_2' = F_1 - \Delta F_1 \tag{28}$$

The new leader force should result in smaller joint torques that need to be provided by the leader. As a result, the position error of the object can be reduced.

4. Simulation Results

To verify the force compensation method as proposed in the previous section, computer simulation was conducted in our study. We assume that two PUMA 560 robots are coordinated to move an object with a mass of 8 Kg (the maximum load of a single PUMA is 4 Kg). However, the mass is unknown to the robot. A motion trajectory is then selected for the object. Based on the motion of the object and the parameters of PUMA, required joint torques are calculated for the leader. Fig. 4 shows those required torques.

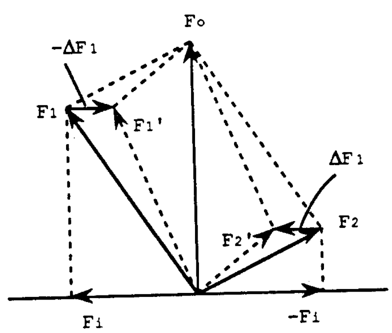

Fig. 3 The changing of the end-effector's forces after the force compensation

We also assume that the limit of the joint torque is 3 Nm. By inspecting Fig. 4, it can be found that the required torque of joint 6 exceeds its limit. Therefore, the torque needs to be compensated.

It is clear that the result of an excessive load is a large position error. We select 0.004 inch as the position error bound (0.004 inch is the position precision of PUMA 560). When the error exceeds the bound, the method as described in the previous section is engaged. The goal is to reduce the required torque of joint 6. By using the compensation method, the result is shown in Fig. 5. It can be shown in Fig. 5, that required torque of joint 6 never exceeds 3 Nm. It is noted that when the compensation force is active, the magnitudes of all the joint torques are reduced. This is because the compensation actually provides a quantity of **DT1** as shown in (24) not just T_6, although the error is originally caused by T_6.

5. Conclusion

In this paper, the unknown load distribution problem is studied. Two different approaches are used to solve the problem of unknown load distribution. The first approach estimates the load using two wrist force sensors. Then previous methods for optimal load distribution can be applied.

The second approach the follower to provide a force compensation when the leader is overloaded In this method, the leader's position error, which is caused by overloading of the leader joint torque, is transformed to an additional torque value. This additional torque is compensated by the follower. First the additional torque requirement is transformed into the reaction force of the follower. Then, using the force control strategy, the load on the leader is reduced. As a result, the leader can follow the desired motion trajectory of the object. Simulation results are provide for the force compensation method which prove that the proposed method is valid.

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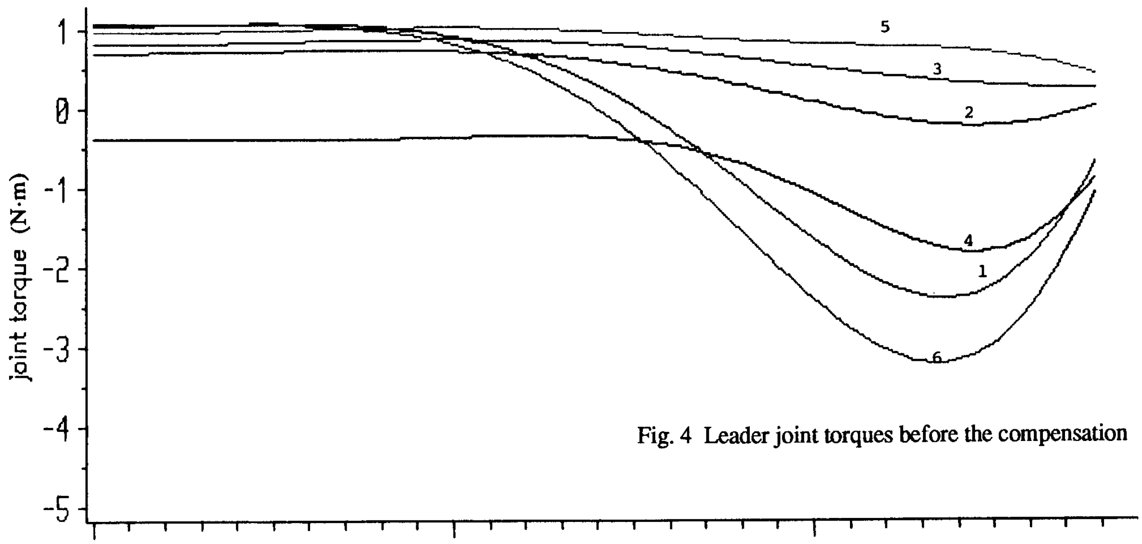

Fig. 4 Leader joint torques before the compensation

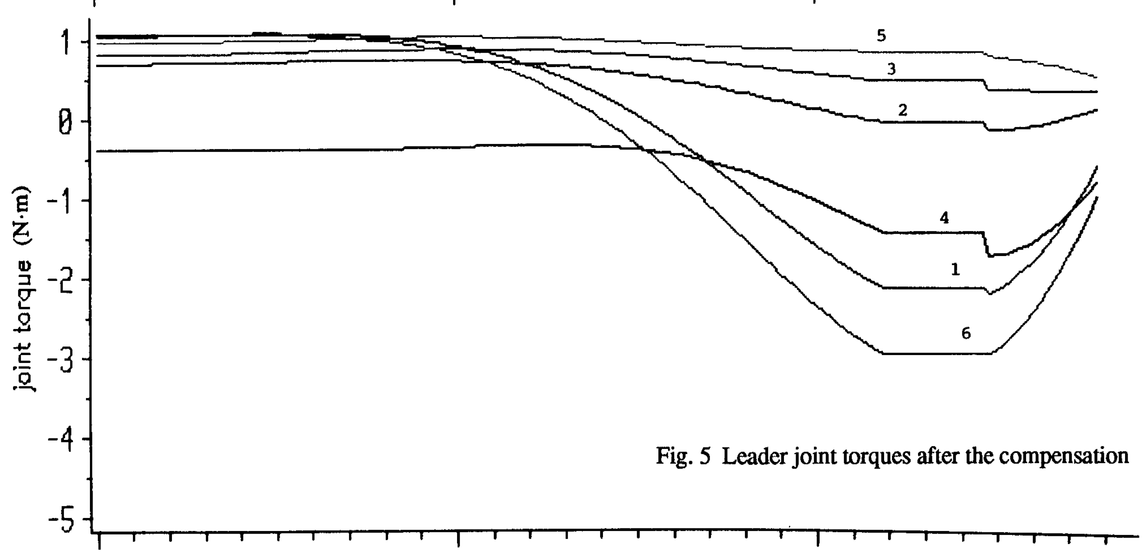

Fig. 5 Leader joint torques after the compensation

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