Two Strategies for Handling Unknown Loads of Two Coordinating Robots

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(Received March 26, 1998)

In real situations, a robotic system can work in an unstructured environment in which the load is often unknown. This problem is an under-studied one, especially for multi-robot systems. In this paper we solve this problem by the 'Unknown Load Distribution' method for two coordinated industrial robots. Two methods are proposed for the distribution of an unknown load. The first method is called 'load estimated method', in which the parameters associated with the load are estimated using the information provided by two wrist force sensors. As a result, the load becomes known, and conventional optimal load distribution methods can then be applied to distribute the force. The second method is called the 'force compensation method', in which one of the robots (the leader) takes the major role of carrying the load to the exact location and the other robot (the follower) follows the leader with a specified force. The load is compensated by the follower using force control until the leader can carry the load to follow a satisfactory trajectory. To verify the force compensation method, a computer simulation is conducted.


1. Introduction

The load distribution problem was previously studied by a number of papers for multiple manipulators (Zheng and Luh, 1988; Luh and Zheng, 1988; Cheng and Olin, 1989; Olim and Oh, 1981; Kreutz and Lokshin, 1988; Kumar and Waldron, 1988; Hsu, 1989; Walker et al., 1989; Pittelkau, 1988; Wang and Rami, 1988; Shin and Makay, 1987; Walker et al., 1989; Yoshikawa and Sudou, 1990) and multi-finger hands (Demmel and Lafferriere, 1989; Park and Starr, 1989; Cole et al., 1989; Murray and Sastry, 1989; Li et al., 1989; Kerr and Roth, 1986; Arimoto et al., 1987; Yoshikawa and Nagai, 1987). In general, these 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 (1981) 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 used to obtain a solution. More recently, Zheng and Luh (1988) proposed several distribution methods for two coordinated manipulators using a number of criteria, including least energy consumption, minimum force exertion on the end-effectors, etc.

In most of the previous studies, the load mass and inertia are 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. Shin and Mckay (1987) address the robust trajectory-planning problem for a single manipulator under payload uncertainty. Walker et al. (1989) propose the adaptive coordinated motion control of two arms with unknown load
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mass. Yoshikawa and Sudou (1990) deals with
the on-line estimation of unknown constraints.
Atkeson et al. (1986) estimated the load param-
eters in the one arm case using a wrist force sensor.
In this paper, the unknown load problem for two
coordinated arms is analyzed and simulated.

We propose two methods for load distribution
among two industrial robots. The first method is
called 'load estimation method' and the second
method is called 'force compensation method'.
In the load estimation method, the load is estimated
by using two wrist force sensors installed in each
robot. Once the load is estimated, then all the
distribution methods previously developed in the
other works can be used. Our method will be an
extension of the methods developed for load
estimation of a single manipulator as studied in
(Atkeson et al., 1986).

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

The organization of the paper is as follows. In
Section 2, load estimation by two industrial
robots is first studied. In Section 3, our study is
concentrated on the force compensation method.
Simulation results for the force compensation
method are presented in the Section 4, followed
by the conclusions.

2. Load Estimation Method

Load estimation was previously studied for a
single robot arm in (Atkeson et al., 1986), in
which a wrist force sensor was used to estimate
the force. In our study, the estimation method of
(Atkeson et al., 1986) 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, robot 1 is labelled as the
leader, and robot 2 as the follower. We first derive
the Newton–Euler equations for the two robots
holding one rigid object (Fig. 1). From Fig. 1, it
can be seen that Newton's equation for the load is

\[ f_1 - f_2 + m_c \cdot g - m_c \cdot \dot{x}_c = 0 \]

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,
\( \dot{x}_c \) : 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

\[ N_1 - N_2 - (r_1 + r_2) x f_1 + r_2 x f_2 - I_e \cdot \omega_c
- \omega_c \times (I_e \cdot \omega_c) = 0 \]

where \( N_1, N_2 \) are the moments of the leader and
follower end-effectors, respectively,
\( r_1, r_2 \) are the position vector from leader
to follower and follower to centroid, respectively,
\( I_e \) : the centroidal inertia tensor of load,
\( \omega_c \), \( \dot{\omega}_c \) are the rotational velocity and the
acceleration of the load, respectively and
\( \times \) is the vector product.

As for the kinematics, the following transforma-
tion relation can be obtained from Fig. 1:

\[ X = T_1^{-1} \cdot Z \cdot T_2 \]

where \( T_1, T_2 \) are \( 4 \times 4 \) homogeneous transforma-