Automatica 45 (2009) 333–342

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

# Human–robot collaboration in precise positioning of a three-dimensional object☆

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ARTICLE INFO

*Article history:*
Received 11 October 2007
Received in revised form
20 June 2008
Accepted 13 August 2008
Available online 4 January 2009

*Keywords:*
Human–machine interface
Assembly robots
Industrial robots
Robot control
Power assisted control

ABSTRACT

This paper deals with fundamental issues of human–robot cooperation in precise positioning of a flat object on a target. Based on the analysis of human–human interaction, two cooperation schemes are introduced. Several algorithms implementing these schemes are developed. A general theoretical framework for human/robot cooperation has been developed to represent these algorithms. The evaluation of the algorithms was carried out using our in-house made robot prototype and experiments by human subjects has demonstrated the effectiveness of our schemes. The main problem was the regulation of the robot-human interaction. Since the robot has no range sensors, it has to rely on the force and displacement information resulting from the interaction with human to understand human intention. The way the robot interprets these signal is crucial for smooth interaction. To be able to carry out a concrete task a simplification was made, in which robot and human do not directly hold the object but a frame to which the object and various sensors are attached.



## 1. Introduction

The robot working space and the human working space are usually strictly separated in industry. However direct cooperation between robots and humans would open new horizons of man/machine interface and completely change human life style and environment. We have focused on an example of robot–human cooperation which is precise positioning of a flat object on a target. This kind of task normally carried out by two humans can often be found in industrial production halls. The training period for workers is long and costly. Each worker duo has to train together before acquiring enough skills to be able to work on the assembly line. There are cases when two workers cannot accomplish the task together in spite of long period of training. The development of a robot that would be able to replace one of the workers would solve this bottleneck problem of industrial assembly. The main issue of this paper is to analyze cooperation principles and to give communication guidelines for robot–human cooperation for precise positioning from control point of view. The principles of robot–human cooperation obtained in this research can be applied to many other tasks where robot and human need to work together with continued direct contact. We have focused on an industrial application which is windscreen assembly on a car body that is moving on a production line conveyor belt.

We are dealing with robot–human cooperation where the robot has no range sensors to detect the position of the target. In such a situation the robot has to rely on the force and displacement information that is the direct result of interaction with a human.

In a scenario where a human and a robot hold an object and manipulate it, a question arises how should robot interpret human movements and read human intentions. The most basic problem at the level of physical contact is how the robot should distinguish whether the human wants to rotate the object or translate it laterally. We call this problem *translation/rotation problem*. Based on our human–human cooperation analysis we are going to derive algorithms that solve this problem.

Because of the robot's lack of range sensors, the human has to take over much of the decision making during the manipulation task. This puts a too large burden on the human who has to concentrate on all six degrees of freedom (d.o.f.) of the object. To lighten this burden, we proposed concentration aiding schemes. These are: The *four-corner display* that shows different parts of the object on one screen. Another scheme is the use of switched algorithms that allow the human to decide different d.o.f.

☆ This paper was partially presented at IFAC 2008. This paper was recommended for publication in revised form by Associate Editor Jae-Bok Song under the direction of Editor Toshiharu Sugie.

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0005-1098/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2008.08.021

depending on situation. The four-corner display focuses human concentration in space and the *switched algorithms* split humans concentration in time.

### 1.1. Related research

There is a great deal of robot–robot cooperation research (Gao, Dawson, & Qu, 1992), but only few researchers focus on human–robot cooperation for object manipulation. Most of them deal, however, only with the manipulation but not with intelligent task such as the precise positioning introduced in this paper. The rotation/translation problem is tackled only by few researchers. Many of them use a kind of switch or automatic switching between two modes, a rotation mode and a translation mode. In Yokoyama et al. (2003) the modes are switched by human command. In Takubo, Arai, Hayashibara, and Tanie (2002b), Takubo, Arai, Tanie, and Hayashibara (2000), Takubo, Arai, and Tanie (2002c) and Takubo, Arai, Hayashibara, and Tanie (2002a) the problem was tackled indirectly. By using nonholonomic constraints the object behaves as a unicycle. Therefore, the objects cannot be moved sideways directly. To move it to the side, a combination of front–back translations and rotations has to be carried out. This kind of manipulation cannot be applied to our case because of the lack of space and time for maneuvers. In Kosuge, Kakuya, and Hirata (2001) and Kosuge, Kakuya, and Hirata (2001) the robot Mr Helper is supporting the whole weight of the object and the human has his hands free to apply intentional forces to move the object. He can change the position of his hands at any time. In Ikeura, Inooka, and Mizutani (2002) the interaction of two humans is investigated and later one of them, the follower, is modeled as impedance and a robot is designed based on this model. No rotation/translation problem seems to be addressed. In Yigit, Burghart, and Woern (2003) and Osswald, Yigit, Kerpa, Burghart, and Woern (2003), robot–human interaction is investigated, but again the human can place his hands anywhere on the object and push it into the desired direction. The situation is different in our case. The human must hold handle from the beginning of the positioning task to its end.

To the best of our knowledge no research addresses precise positioning. The main aim of our project is not the transport but the cooperative precise positioning of a large object on a target within limited time. This kind of task often appears in assembly lines of production halls.

### 1.2. Content

In Section 2 we analyze human–human cooperation and formulate a theoretical framework for robot–human manipulation from a control point of view. In Section 3 we describe the concrete application we are dealing with. We analyze human–human cooperation further and define two cooperation schemes, the *d.o.f. separation* cooperation and the *weight separation* cooperation. The problem of human concentration during the assembly is pointed out. A tool that helps the human to focus his concentration, the four-corner display, is introduced. Also, switched algorithms are presented as an aid to help the human to concentrate on fewer d.o.f. at a time. In Section 4 robot–human cooperation algorithms imitating the previously found cooperation schemes are presented. We distinguish between algorithms with switch, *switched*, and without switch, *switchless*. In Section 5 the cooperative robot prototype is introduced, the experimental settings and results are shown and discussed. The partner-that-follows algorithm reveals to be the best one for our application.

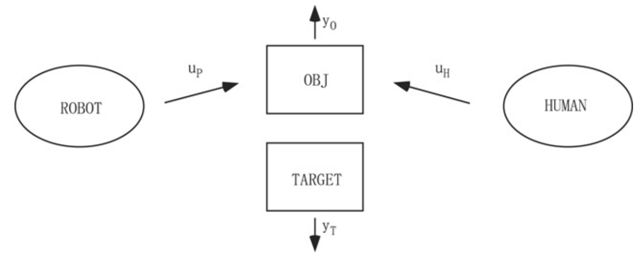


**Fig. 1.** Human and robot acting on an object.

## 2. Theoretical framework of human–robot cooperation

### 2.1. General formulation of human–robot cooperation

As schematically shown in Fig. 1 the human and the robot act on an object OBJ. The components of the human and robot input vectors are forces and torques.

$$\mathbf{u}_H = \left(f_{xH}, f_{yH}, f_{zH}, \tau_{\alpha H}, \tau_{\beta H}, \tau_{\gamma H}\right)^{\mathrm{T}} \tag{1}$$

$$\mathbf{u}_P = \left(f_{xP}, f_{yP}, f_{zP}, \tau_{\alpha P}, \tau_{\beta P}, \tau_{\gamma P}\right)^{\mathrm{T}}. \tag{2}$$

Here $f$ denotes force and $\tau$ torque. The index $H$ stands for human and $P$ for partner (in this case a robot). The object position and orientation vector is

$$\mathbf{y}_O = (x_O, y_O, z_O, \alpha_O, \beta_O, \gamma_O)^{\mathrm{T}}. \tag{3}$$

The first three elements $x$, $y$ and $z$ represent the position in a Cartesian coordinate system and the angles $\alpha$, $\beta$ and $\gamma$ are the orientation angles in a certain frame. The angle $\alpha$ denotes rotation around the $x$-axis, $\beta$ around the $y$-axis and $\gamma$ around the $z$-axis.

The target position and orientation is denoted by

$$\mathbf{y}_T = (x_T, y_T, z_T, \alpha_T, \beta_T, \gamma_T)^{\mathrm{T}}. \tag{4}$$

We express the robot–human interaction generally as

$$\mathbf{y}_O = \mathbf{K}\left(\mathbf{u}_{\mathrm{P}}, \mathbf{u}_{\mathrm{H}}\right) \tag{5}$$

for some nonlinear operator **K**.

The objective of human–robot cooperation is reduced to find an appropriate operator **K** that describes the way the robot and the human act on the object. This function includes the object properties as well as geometrical configurations. The theoretical framework described in this paper does not depend on the object's shape, but only on the points the human and the robot apply forces and torques on the object. In this paper, we assume a rectangular-shaped object.

### 2.2. Constraints

In the general ideal case, both the human and the robot, can exert forces and torques on the object. We introduce a human coordinate system with origin at point $H$ and partner coordinate system with origin at point $P$ as illustrated in Fig. 2. The Figure is a prismatic view of a flat, rectangular-shaped object with the geometrical center $M$. The human applies forces and torques on the point $H$ and the robot on the point $P$. The vectors $\mathbf{u}_H$ and $\mathbf{u}_P$ consist of three forces and three torques each. These are 12 inputs to an object that has only six d.o.f. Thus, the force in the front–back direction ($y$-direction) is the same in both the robot and the human output vector

$$f_{yH} = f_{yP}. \tag{6}$$

Also the torque exerted around the axis going through points $H$ and $P$ ($y$-axis) are the same for the robot and for the human

$$\tau_{\beta H} = \tau_{\beta P}. \tag{7}$$