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Human-Robot Cooperation in Precise Positioning of a Flat Object

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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 defined. An algorithm imitating one of these schemes is presented. A general mathematical framework for human/robot cooperation has been developed, based on which several algorithms are proposed. The evaluation of the algorithms was carried out using our in-house made robot prototype using a number of subjects has demonstrated the effectiveness of our ideas. 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. 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. Based on our research results, we succeeded in installing a commercial platform.

Keywords: human-machine interface, assembly robots, industrial robots, robot control, power assisted control,

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 bottle neck 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. We developed a commercial platform for an industrial application which is wind screen assembly on a car body that is moving on a production line conveyor belt.

1.1 Difficulties

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 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 derived 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.

1.2 Related Research

There is a great deal of robot-robot cooperation research Gao et al. [1992] but only few research in human-robot cooperation for object manipulation. Most of it deals, however, only with the manipulation but not with intelligent task like 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. [September 14-19, 2003] the modes are switched by human command. In Takubo et al. [May-June 2002] the problem was tackled indirectly. By using nonholonomic constraints the object

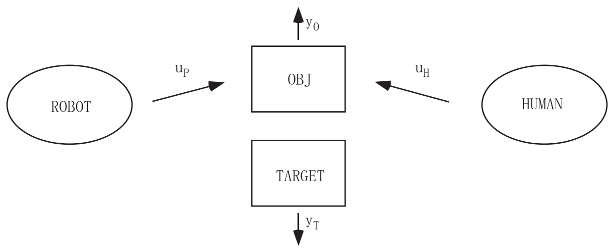

Fig. 1. Human and robot acting on an object

behaves like 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 in our case because of the lack of space and time for maneuvers. In Kosuge et al. [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 anytime. In Ikeura et al. [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 et al. [August 2003] and Osswald et al. [March 2003], robot-human interaction is investigated, but again 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.

1.3 Content

In Section 2 we analyze human-human cooperation and formulate a theoretical framework for robot-human manipulation from control point of view. In Section 3 we describe the concrete application we are dealing with. We analyze further human-human cooperation and define two cooperation schemes, the *d.o.f. separation* cooperation and the *weight separation* cooperation. A robot-human cooperation algorithm derived from one of the before found cooperation schemes is presented. In Section 5 the cooperative robot prototype is introduced, the experimental settings and results are shown and discussed. The partner-that-follows algorithm revealed to be the best one for our application.

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.

$$\mathbf{u_H} = (f_{xH}, f_{yH}, f_{zH}, \tau_{\alpha H}, \tau_{\beta H}, \tau_{\gamma H})^T \qquad (1)$$

$$\mathbf{u_P} = (f_{xP}, f_{yP}, f_{zP}, \tau_{\alpha P}, \tau_{\beta P}, \tau_{\gamma P})^T \qquad (2)$$

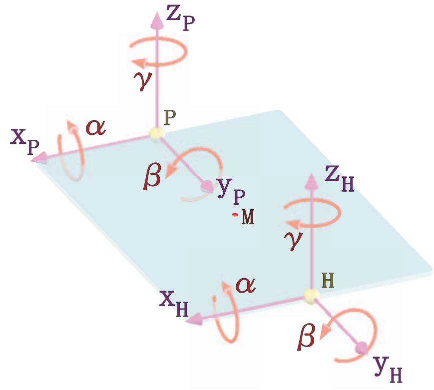

Fig. 2. Object fixed Human and Partner coordinate system

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

$$\mathbf{y_O} = (x_O, y_O, z_O, \alpha_O, \beta_O, \gamma_O)^T \qquad (3)$$

The first three elements x, y and z represent position in a Cartesian coordinate system and the angles α, β and γ are the orientation angles in a certain frame. The angle α denotes rotation around the x-axis, β around the y-axis and γ around the z-axis.

The target position and orientation is

$$\mathbf{y_T} = (x_T, y_T, z_T, \alpha_T, \beta_T, \gamma_T)^T \qquad (4)$$

We express the robot-human cooperation scheme generally as

$$\mathbf{y_O} = \mathbf{K}(\mathbf{u}_\mathrm{P}, \mathbf{u}_\mathrm{H}) \qquad (5)$$

for some nonlinear function $\mathbf{K}$.

The objective of human-robot cooperation is reduced to find an appropriate function $\mathbf{K}$ 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 here described theoretical framework doesn't depend on the objects 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 in point H and partner coordinate system with origin in point P as illustrated in Fig. 2. The Figure is a prismatic view of a flat, rectangular-shaped object with the geometrical center M. 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

$$f_{yH} = f_{yP} \qquad (6)$$

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

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

After further analysis we can see that the torque exerted by the robot around the vertical going through point P has the same effect as a force exerted by human on the point H in the lateral direction (x-direction). We can find four such torque-force pairs

$$\begin{aligned} \tau_{\alpha H} &= D_{PH} f_{zP} \\ \tau_{\gamma H} &= D_{PH} f_{xP} \end{aligned} \tag{8}$$

$$\begin{aligned} \tau_{\alpha P} &= D_{PH} f_{zH} \\ \tau_{\gamma P} &= D_{PH} f_{xH} \end{aligned} \tag{9}$$

where D_{PH} is the constant distance between the point H and the point P. The six constraints, Eqs. 6-9, reduces the number of independent inputs to six. Human and robot can influence all six d.o.f. of the object. For a smooth conflict-less cooperation, a way of acting has to be regulated or a priori decided by imposing constraints.

2.3 Human Partner

Let us imagine two persons holding an object. One person stands at point P and the other one at point H. Each holds a handle that is attached to the object. Analyzing person H we can quickly find out that he is not able to produce any large torques $\tau_{\alpha H}$ around the x_H-axis. Torques $\tau_{\gamma H}$ around the z_H-axis produced by person H are not large enough to affect person P. Only torques $\tau_{\beta H}$ around the y_H-axis, that person H produces, can be felt by person P. Person H can exert any forces along the three directions where forces f_{xH} and f_{zH} along axes x_H and z_H respectively are perceived by person P as torques $\tau_{\alpha P}$ and τ_γ respectively as can be seen from Eq. 8. Only force f_{yH} along y_H axis can be felt by person P as force as shown in Eq. 6. A good robot partner doesn't necessarily have to be an imitation of a human partner so we can design a robot that is able to produce torques. However, the joints and its actuators would have to be extremely strong to withstand the torques that arise when the human applies forces to the object.

To avoid a bulky robot structure we can equip the robot with a free joint, a three d.o.f. unactuated ball joint. This is exactly what a simplified model of a human partner would be. It is a robot that can exert only forces but no torques. The free joint has three rotations denoted by α, β and γ as shown in Fig. 5. The free joint is therefore defined by $\tau_{\alpha P} = 0$, $\tau_{\beta P} = 0$ and $\tau_{\gamma P} = 0$ which reduces the vector $\mathbf{u_P}$ in Eq. 2 to $(f_{xP}, f_{yP}, f_{zP})^T$.

2.4 Mathematical Description of Manipulation

Whereas Fig. 1 illustrates a very general scheme of co-operation here we get more concrete and describe the whole system in a block diagram as shown in Fig. 3. The Object OBJ receives two inputs, the human input $\mathbf{u}_H$ and the robot partner ROB input $\mathbf{u}_P$. The robot controller closes a local loop. The object and the robot together can be regarded as one system and described by a function $\mathbf{Q}(\mathbf{u}_{Pref}, \mathbf{u}_H)$. The reference signal to the robot is generated by the algorithm ALG from the measured information of the object $\mathbf{y}_m$. We assume that the position and orientation of the object $\mathbf{y}_O$ can be directly measured or if not calculated from other measured signals y_m. In addition we assume that some forces or torques exerted on the object can be measured. All the measured data is contained in the vector $\mathbf{y}_m$.

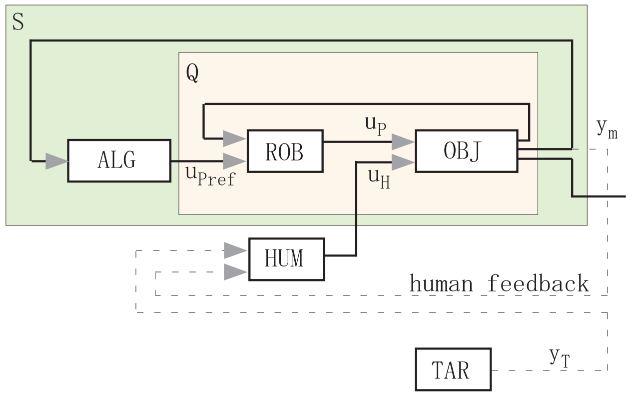

Fig. 3. System Block Diagram

We define the algorithm ALG as the relation between the available sensor outputs

$$\mathbf{y}_m = (x_P, y_P, z_P, \alpha, \beta, \gamma, f_y, \tau_{Hz})^T \tag{10}$$

and the reference input to the robot $\mathbf{u}_{Pref}$. Here x,y and z represent the position of the free joint the point P. The angles α,β and γ are also measured at the free joint but since we deal with a rigid body the angles are same independent from the position. We also measures the force f_y in the front back direction and the torque τ_{Hz} at the human side around the object normal. The vector y_m can be defined in different ways depending on position of sensors and robot structure. The reference input to the robot

$$\mathbf{u}_{Pref} = (v_{Prefx}, f_{Prefy}, v_{Prefz})^T \tag{11}$$

where v denotes velocity and f force. We described the algorithm ALG as a nonlinear operator

$$\mathbf{u}_{\mathrm{Pref}} = \mathbf{H}(\mathbf{y}_m) \tag{12}$$

The object together with the robot and its local controller is defined as

$$\mathbf{y}_m = \mathbf{Q}(\mathbf{u}_{\mathrm{Pref}}, \mathbf{u}_{\mathrm{H}}) \tag{13}$$

It takes $\mathbf{u}_{Pref}$ and human forces and torques $\mathbf{u}_H$ as input and gives $\mathbf{y}_m$. We assume the functions $\mathbf{Q}$ and $\mathbf{H}$ to be of linear dynamics and write it as transfer function matrices $\mathbf{Q}(\mathbf{s})$ and $\mathbf{H}(\mathbf{s})$, respectively. We split $\mathbf{Q}(s)$ into two parts, one depending on human $\mathbf{Q}_H(s)$ and one depending on the algorithm $\mathbf{Q}_{Pref}(s)$. If Eqs. 12 and 13 are linear

$$\mathbf{y}_m = \left[\, \mathbf{Q}_{\mathrm{Pref}}(s) \;\; \mathbf{Q}_{\mathrm{H}}(s) \,\right] \begin{bmatrix} \mathbf{u}_{\mathrm{Pref}} \\ \mathbf{u}_{\mathrm{H}} \end{bmatrix} \tag{14}$$

After inserting Eq. 12 into Eq. 14 we get

$$\mathbf{y}_m = \mathbf{Q}_{\mathrm{Pref}}(s)\,\mathbf{H}(s) + \mathbf{Q}_{\mathrm{H}}(s)\,\mathbf{u}_{\mathrm{H}} \tag{15}$$

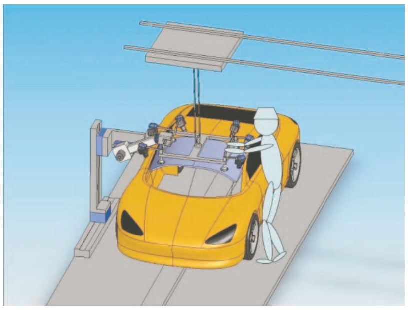

Fig. 4. Human and robot attaching a windshield on a car body

Expressing $\mathbf{y}_m$ explicitly gives

$$\mathbf{y}_m = \left(\mathbf{I} - \mathbf{Q}_{\mathrm{Pref}}\left(s\right)\mathbf{H}\left(s\right)\right)^{-1}\mathbf{Q}_{\mathrm{H}}\left(s\right)\mathbf{u}_{\mathrm{H}} \tag{16}$$

We can express the whole system with a single matrix.

$$\mathbf{y}_m = \mathbf{S}\left(s\right)\mathbf{u}_{\mathrm{H}} \tag{17}$$

Here $\mathbf{S}(\mathbf{s})$ is the transfer function matrix of the whole system where the input is the human forces and torques. An appropriate algorithm $\mathbf{H}(\mathbf{s})$ is to be designed so that the overall system matrix

$$\mathbf{S}\left(s\right) = \left(\mathbf{I} - \mathbf{Q}_{\mathrm{Pref}}\left(s\right)\mathbf{H}\left(s\right)\right)^{-1}\mathbf{Q}_{\mathrm{H}}\left(s\right) \tag{18}$$

is desirable. Note that the above representation can only be used if the dynamics is linear or can be linearized.

3. DESCRIPTION OF TASK

We have focused on an industrial application which is the assembly of a wind screen on a car body. A human worker and a robot have to position a wind screen on a car body as shown in Fig. 4. The car body is moving on an assembly line. Since the assembly has to be carried out on a moving conveyor belt the task has to be done promptly.

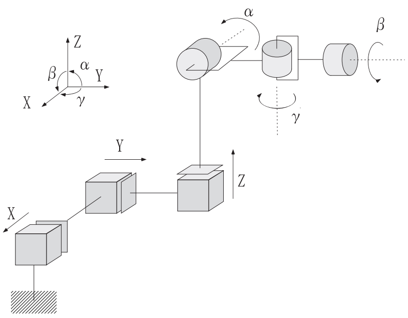

Fig. 5. Robot Kinematics

3.1 Cooperation Schemes

We distinguish two mechanisms in cooperation. One we call *d.o.f. separation cooperation* and the other one *weight separation cooperation.*

D.o.f. Separation If the system has a total of n degrees of freedom, the robot is in charge of r d.o.f., while the human is in charge of the remaining $n-r$ degrees of freedom, then we speak of d.o.f. separation cooperation. An example would be the positioning of an object where the x-direction is manipulated by only the human input vector while the rotation around the objects normal is manipulated by only the robot input vector, i.e.,

$$\begin{aligned} x_O &= f_1\left(\mathbf{u_H}\right), \\ \gamma_O &= f_2\left(\mathbf{u_P}\right), \end{aligned} \tag{19}$$

for some functions f_1 and f_2.

In human-human cooperation it have been observed that if we have an experienced worker and a beginner, d.o.f.-separation cooperation takes place. One worker is in charge of rotations, while the other one of translations In Reed et al. [April 2004] the authors describe the phenomena of specialization on a very simply example.

Weight Separation Another way of cooperating is to split a d.o.f. by weighting. A single d.o.f. is acted on by both parties.

$$y_O = w_1 f_1\left(\mathbf{u_H}\right) + w_2 f_2\left(\mathbf{u_P}\right) \tag{20}$$

with $w_1 + w_2 = 1$. The non-negative parameters w_1, w_2 denote weights. Depending on the weights, human and robot have more or less competence to perform a movement in this d.o.f.. The mechanical structure of the robot can also dictate the way the robot acts on the object and so dictate the way robot and human cooperate.

In the front-back direction (y-axis) both workers share a single degree of freedom. Weight separation cooperation takes place. The assembly task can be accomplished without mutual disturbance if one of them becomes the leader and the other the follower. Carrying out an assembly task in a production hall a quick force communication between two humans can be observed. To be able to understand each other both humans have to train for quite a long time. A pair of well trained workers can achieve positioning accuracies in submillimeter level. The humans obviously learn to transform the positioning error into force signal that the human on the other side of the object can interpret. So each worker can see the positioning error on his side and can feel the positioning error on the other side through the force in front-back direction. In case of human workers it also happens that certain two workers do not form a good pair and cannot position the object within prescribed time and precision limits.

4. COOPERATION ALGORITHMS

4.1 Switched Algorithms

The rotation-translation problem disappears when d.o.f. separation is applied. A direct implementation of these are the switched algorithms that are not the main subject of this paper. In the switched algorithms, the human is in charge of the rotation and the robot in charge of the translations. When the mode is switched the roles are changing, the human is in charge of translations and the robot in charge of rotation. Using a switch seems not to be natural and so a we developed algorithms without switch. In this paper we mention two of the switchless algorithms, the NORMAL and the BETA algorithm to contrast with the below described switched algorithms.

4.2 Switchless Algorithms

In the switch-less algorithms, we measure torques that human exerts on the object and use them as information to read his intention. Unlike in the switched algorithms here we do not switch between the two modes. In the parter-that-follows algorithm the displacement information is used to control the translation mode and the torque information to control the rotation mode. We introduce one switchless algorithm that we call partner-that-follows algorithm.

Partner-that-Follows Algorithm If we imagine two people manipulating a large but lightweight piece of furniture on the floor and we assume that one of them is a leader and the other one a follower the actual movement of the object will depend on both the leader and the follower. The follower's input vector depends much on his interpretation what the leader wants to do with the object. If the follower assumes that the leader wants to translate the object along the x-direction then every time the leader moves along the x-axis the follower moves too. This algorithm is called partner-that-follows and it's the one that turns out to be best for our application. The control law in x and z direction is

$$\begin{aligned} v_{Px} &= c_x\gamma - c_\tau \frac{\mathrm{d}}{\mathrm{dt}} \cos\beta \\ v_{Pz} &= c_z\alpha + c_\tau \frac{\mathrm{d}}{\mathrm{dt}} \sin\beta \end{aligned} \tag{21}$$

The control law in the y-direction is

$$f_{Py} = \frac{\mathrm{dy}}{\mathrm{dt}} d_{yR} + m_{yR}\,\tau_{Hz} \tag{22}$$

where d_{yR} is the damping m_{yR} is the mass parameter of the compliance control.

The algorithm in matrix formulation is

$$\mathbf{H}(s) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & c_x & 0 & -\dfrac{c_\tau \cos\beta}{s} \\ 0 & d_{yR}s + k_{yR}(z) & 0 & 0 & 0 & 0 & m_{yR} & 0 \\ 0 & 0 & 0 & c_z & 0 & 0 & 0 & \dfrac{c_\tau \sin\beta}{s} \end{bmatrix} \tag{23}$$

Here the c_x, c_z, and c_τ are constant control parameters that were set as to satisfy the humans feeling for robots speed in response to his input. The matrix contains non-linear elements in β and z and therefore the matrix representation is not appropriate. Still the matrix is a way of expressing the algorithm in a way that can be easily compared with other algorithms in matrix form. The The last elements of the $\mathbf{H}$ matrix contain integration of torque τ_{Hz} and so play the role of memory. When no torques applied the angles are kept constant. Applying torques changes the angles to be kept by the robot.

The resulting, ideal system behavior can most conveniently be described by redefining u_P as $(\,x_H\ y_H\ z_H\ \tau_{Hx}\ \beta\ \tau_{Hz}\,)$ where x_H, y_H and z_H denote the position of point H, β is the angle around the y axis going through point H and τ_{Hx} and τ_{Hz} are torques applied on point H. The position and orientation of the object's center M, for an object carried parallel to the ground $\beta = 0$, can be calculated from the redefined u_P by multiplying it with the matrix

$$\tilde{\mathbf{S}}(s) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -\dfrac{1}{s} D_{HM} c_\tau \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & \dfrac{1}{s} c_\tau \end{bmatrix} \tag{24}$$

The algorithm implemented in a robot imitates a partner that follows in the x-direction. If the object as in Fig.6 is displaced a distance Δx_H at point H the result is an object that is translated a distance Δx_H along the direction x. If the human wants to rotate the object he has to apply torques on the object.

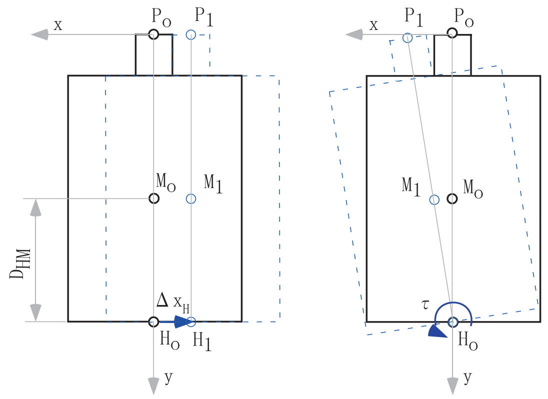

Fig. 6. Partner that Follows Algorithm. Left: translation. Right: rotation

5. SETTING UP AND EXPERIMENTS

5.1 The Prototype

We have developed a prototype robot for cooperative precise positioning of a flat object. The robot has six degrees of freedom. Three prismatic joints are actuated by electrical motors and allow for movements in all three directions of the Cartesian space as shown in Fig. 5. We also have three unactuated revolute joints, which form a free joint. The angles of the revolute joints are measured by rotary encoders. A frame to hold the flat object is used. The industrial application allows us to use this kind of frame. The frame has many advantages like for example a handle can be attached to it. On the production line the object would be attached to the frame below by suction cups or grippers for example. In our prototype however we don't distinguish between object holding frame and the object itself. At the human side of the object holding frame H a handle with a torque sensor is attached. A force sensor at the robot side is used to allow for movements in the front-back direction (y-direction). The complete system and a human are illustrated in Fig. 7. The four devices attached to the top of the object holding frame are cameras that are not subject of this paper. The frame with the handle attached to it is shown more detailed in Fig. 8. The left part is rigidly attached to the robots xyz-stage. The next part is the force sensor measuring forces in the y-direction. A three d.o.f. free joint is attached directly to it. On the right side of the frame the handle is mounted and in it a torque sensor measuring the torque

Fig. 7. The prototype

Table 1. Experimental results -NORMAL-, BETA-, partner-that-follows algorithms

	time	y	x	yaw
BETA	8.0	1.9	1.8	0.11
NORMAL	10.7	2.5	1.9	0.16
partner-follows	9.5	1.3	1.4	0.08
	[s]	[mm]	[mm]	[deg]

τ_{Hz} around the objects normal through point H. We installed a mechanical limit switch that prevents the robot from penetrating the human working space.

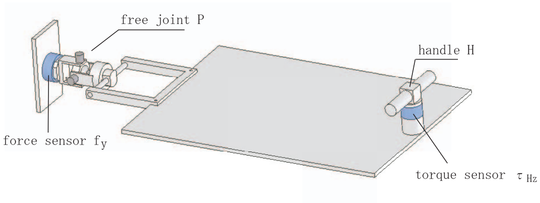

Fig. 8. Object holding frame

5.2 Experiments

Experiments were carried out with three subjects. Each subject was told to move the object from its original position and place it exactly in the middle of the target so that edges are in parallel. Every subject repeated the experiment ten times. The size of the object is $a_O = 470mm$ and $b_O = 670mm$ and the size of the target is $a_T = 478mm$ and $b_T = 678mm$. The subjects had to move the object about $300mm$ along the x-direction, about $200mm$ along the y-direction and from a height of about $1600mm$ to about $1000mm$.

Table 1 compares the experimental results of the partner-that-follows algorithm to other algorithms developed in our laboratory. The table shows averages of time needed for the accomplishment of the task, the averages of y- and z-direction positioning errors and the averages of angular error. The position and angular errors were measured after completed task. As can be seen from the experimental data the BETA-algorithm is the fastest one but the highest precision has been achieved with the partner-that-follows algorithm.

6. CONCLUSIONS

In this paper we presented a mathematical framework for robot-human cooperation. We analyzed human-human cooperation. We classified the cooperation schemes into weight separation and d.o.f. separation cooperation. Based on these schemes we derived few robot-human cooperation algorithms and implemented them on our in-house made robot prototype and proved their effectiveness with experiments. The best results showed the partner-that-follows algorithm. Based on our research results, a new car assembly line of the Toyota Motors Cooperation is being equipped with a cooperation robot. This robot's task is the attaching of a wind screen on the front and rear of a car body, in cooperation with a human. The cooperation scheme presented in this paper has been successfully tested there.

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