2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Human-inspired robot assistant for fast point-to-point movements

B. Corteville, E. Aertbelien, H. Bruyninckx, J. De Schutter, *Member, IEEE*
and H. Van Brussel, *Fellow, IEEE*

***Abstract*— A first step towards truly versatile robot assistants consists of building up experience with simple tasks such as the cooperative manipulation of objects. This paper extends the state-of-the-art by developing an assistant which actively cooperates during the point-to-point transportation of an object. Besides using admittance control to react to interaction forces generated by its operator, the robot estimates the intended human motion and uses this identified motion to move along with the operator. The offered level of assistance can be scaled, which is vital to give the operator the opportunity to gradually learn how to interact with the system. Experiments revealed that, while the robot is programmed to adapt to the human motion, the operator also adapts to the offered assistance. When using the robot assistant the required forces to move the load are greatly reduced and the operators report that the assistance feels comfortable and natural.**

I. INTRODUCTION

Due to the aging society, robots are more and more envisioned as helpers of mankind, closely cooperating with and assisting people in their daily life. If these machines, delivering power and information, can be intuitively controlled and operated by any human, including the elderly and disabled, they could potentially extend these people's working career, help them regain their independence and more generally improve the quality of their life. In workshops, a close cooperation between man and robotic manipulator could lead to higher productivity and improved ergonomics because of the synergy between human intelligence and mechanical power [1].

The robot assistants should be adapted to cooperation with humans and be able to cooperatively execute simple tasks such as helping to move heavy objects. The required direct physical contact between the robot and its operator is still quite new in research and mostly consists of assigning an admittance behavior to the robot so it can react to the forces generated by the operator [2], [5]. However, although compensating for gravity, these *passive* assistants tend to make the job of moving the load even more tiring for the operator, since now he has to supply the energy to move the load *and* the robot.

Looking at two people executing the same task, one called the leader controlling the movement and the other called the helper helping to carry the weight, clarifies what the exact task of the robot assistant should be. In this human-human cooperation, the leader does not have to force the helper to move along. Through a sense of speed, displacement or force, even a blindfolded helper is able to detect the onset of the transportation movement, and will *actively* participate in the task of moving the object. Due to the fact that this helper does not know the exact trajectory of the movement and the involved timing constraints, he cannot hold the object rigidly. Moreover, this compliance is important to give the leader the impression that he is in control [4]. Research has shown that the compliance with which he holds the object mainly consists of damping, while inertial and stiffness effects are ignorable [2].

Making a robot assistant for this cooperative transportation task therefore consists of three main parts: implementing an admittance controller which gives the robot the damping behavior *(section I.A and III)*, online estimation of the intended human motion *(section I.C and V)* and the cooperative execution of this motion *(section I.D and VI)*. During the cooperation the assistance supplied by the robot to the operator should feel as if another human was helping to execute the task. This requires the robot to move 'human-like' or contain human movement characteristics *(section I.B and IV)*.

A. Admittance control

In robotics research it is already known for many years that system resonances and delays in the feedback path of a force controlled robot can lead to serious problems when the robot makes contact with an unknown environment [8]. Stiff environments tend to destabilize most force and admittance controllers. Therefore, special care should be taken in designing these controllers. Since a large robot admittance is favorable for good human-robot interaction, the goal of the controller is to maximize this admittance. However, when a force controlled robot is in contact with some environment (for example a human or a fixed object) the system contains a closed feedback loop [7]. The gain of this loop has to be limited in order to keep the system stable. Since this gain is equal to the product of the impedance of the environment and the admittance of the controlled robot, the maximal robot admittance is limited by the maximal stiffness with which the robot interacts. Research pointed out that the human arm is a passive system [8] and has a certain maximal impedance, occurring when the operator maximally stiffens his arm.In the studied case of the robot assistant, the admittance controller solely creates a damping behavior. The value of this damper should be above a certain limit, limiting the maximal admittance, to guarantee the stability of the system.

All authors are with the Department of Mechanical Engineering, University of Leuven, 3000 Leuven, Belgium. Corresponding author: Hendrik Van Brussel (e-mail: hendrik.vanbrussel@mech.kuleuven.be)

Brecht Corteville is research assistant with the Fund for Scientific Research - Flanders (Belgium) (F.W.O.)

For most hardware platforms however, the minimal damping coefficient which can be achieved still generates a burden too large for the operator when executing fast point-to-point movements [5]. This problem can be solved by letting the robot actively participate during the movement [3].

B. Human motion characteristics

A human point-to-point movement consists of two phases [9]. The first phase consists of a large displacement movement with low accuracy, called the transfer motion, bringing the object closer to the target. The human executes this motion in feed-forward, that is, without cognitive feedback during the motion. When reaching the second phase in which the object is positioned on the target, small corrective movements are added to the transfer motion. These smaller motions are triggered by the human, based on visual and proprioceptive feedback. During the human-human cooperation, the required accuracy and current deviation from the target is unknown to the blindfolded helper, so during the positioning he cannot assist the leader further than compensating for gravitational forces on the load. The transfer motion however, contains a specific characteristic, which can be predicted by the helper.

Research has shown that the transfer motions obey a specific rule [6], [9]. They all are executed approximately along a straight trajectory and with a bell-shaped speed profile. This speed profile is a characteristic of individual and cooperative human motion [1]. This means that the helper will go along with the transfer motion of the leader, once he knows approximately where to and how fast the motion should be. A widely accepted description of the speed profile in neurobiology is based on the 'minimal jerk criterion' [9]. This criterion minimizes the change in acceleration of the movement of the human hand. If the movement takes place along a straight axis Y and starts and stops with zero speed, the position along the trajectory is defined as:

$$y(t) = \Delta y \ f\left(\frac{t-t_0}{\Delta t}\right) + y_0, \tag{1}$$

$$f(\tau) = 6\tau^5 - 15\tau^4 + 10\tau^3, \tag{2}$$

$$\Delta t = t_1 - t_0, \tag{3}$$

$$\Delta y = y_1 - y_0, \tag{4}$$

in which y_0, t_0 and y_1, t_1 are the position and time at the beginning and at the end of the motion.

C. Estimation of the transfer motion

When a blindfolded helper is holding the load, he is continuously monitoring the motion of the leader. Once he detects a trigger (based on displacement, speed or interaction force), indicating that the movement has started, he will execute a going-along motion to move along with the leader. However, at first it is not clear for the helper where to and how fast the leader is moving. During the movement he will try to guess these parameters based on an unconscious knowledge of the characteristics of the motion of the leader. This guessing has to be formalized into the robot controller by using an estimation algorithm. This algorithm contains the description of the bell-shaped speed profile and tries to estimate the unknown parameters, resulting in an estimated going-along speed (v_{est}).

D. Generation of the cooperative movement

The estimated going-along motion can now be used in the controller of the artificial robotic assistant to change the reference trajectory of the admittance controller. Additionally, because the admittance controller only contains damping (c_{adm}), *the level of assistance can be scaled*. This is illustrated in figure 1. In the case of a passive assistant, the operator has to generate a force $F = c_{adm} v_{operator}$ to move the robot, shown in figure 1 as the sum of the single and double hatched area. The amount of energy required for this movement equals $W = \int F v_{operator} dt$. However, when (a fraction α of) the estimated going-along speed is used to change the reference position of the admittance controller, it seems as if the damper c_{adm} is no longer fixed to ground, but (partially) moves along with the operator. The operator has to generate a force $F = c_{adm}(v_{operator} - v_{robot})$, which is illustrated in figure 1 as the double hatched area. It is clear that, depending on the used scaling factor α, the amount of energy required for the movement can be tuned. For a level of assistance α equal to 0%, the assistant is passive and the operator has to supply all the energy to move the load. On the other hand, with α equal to 100%, theoretically the robot assistant will independently take care of the complete task. Of course this is practically impossible since the system needs some input from the operator to trigger and estimate the going-along motion. If the level of assistance is between 0% and 100%, the operator and the robot cooperatively execute the task and both have to generate a part of the energy required to move the load.

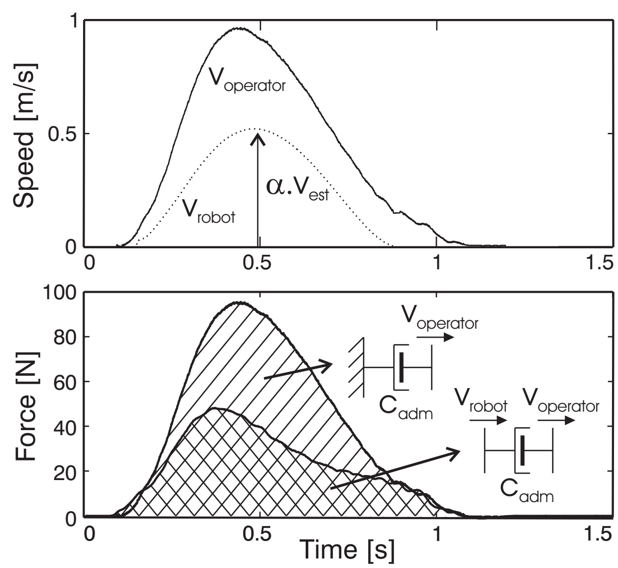

Fig. 1. The interaction force during cooperation

If the admittance controller would also contain stiffness (as in [3]), the scaling would not be so straight-forward since in this case the used going-along motion always has to end at the target point of the movement.

E. Contents of the paper

The cooperative motion investigated in this paper consists of a one dimensional point-to-point positioning task in which the robot tries to support the operator during the transfer motion. The robot is constructed as an actuated one-dimensional horizontal slide with a handle. Besides the mass of the slide, there is no additional load which has to be moved. The location of the starting point and target is marked on the linear slide. These two points are considered to be known to the robot assistant. First, the admittance controller is implemented. Second, it is investigated which speed profile, used to generate the going-along motion of the robot, creates the most natural feeling of assistance for the operator. Next, a Kalman filter which estimates the parameters of the speed profile is implemented and in the last section the cooperation between the operator and the robot assistant is evaluated. The experimental results are obtained by experiments executed by only a limited number of people acting as operators. Therefore the conclusions cannot be considered absolutely user-independent.

II. The experimental setup

The one-dimensional linear setup can be seen in figure 2. The system is actuated by a 200 Watt DC servo motor and the generated motion is transferred from rotational to linear motion by means of a timing belt. This timing belt moves a slide running over a linear guideway. The motor can generate a maximum force of 100 N on the slide. The position of the motor is measured by an optical incremental encoder. On the slide, a handle is mounted allowing the operator to move the slide by pushing the handle. Between the handle and the slide, a force sensor measures the force exerted on the handle. This measured force is used to actively control the movement of the slide. The current through the motor coils is controlled by a power module with a bandwidth of 5 kHz. The robot controller is implemented on a dSPACE control system and the software is automatically generated from a Simulink® diagram.

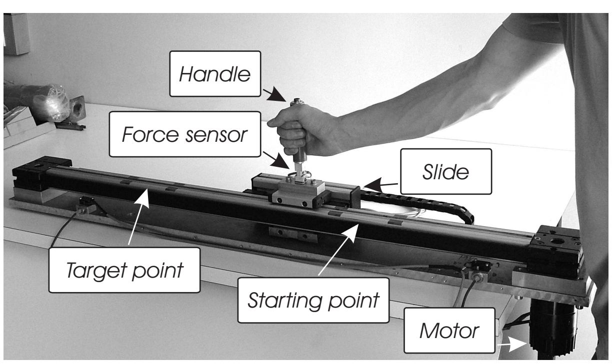

Fig. 2. The experimental setup

III. The admittance controller

The controller will be implemented as a cascaded controller with inner position loop and outer admittance loop. Before designing these control loops, it is necessary to experimentally identify the dynamic parameters of the used setup.

A. Experimental identification of the setup

For identification purposes, a calibrated mass (m_{handle}) is mounted on the handle and the system is modeled as a 6th-order mass-spring-damper system (figure 3). The system has two inputs; the torque generated by the motor (F_{motor}) and the force applied to the handle (F_{handle}) and three outputs; the position of the motor (x_{motor}), the position of the slide (x_{slide}) and the position of the handle (x_{handle}). In the model, all movements and other physical quantities are converted to their linear equivalent, so for instance the rotating motor inertia is converted to a translating mass. During the identification experiment the force exerted on the handle is zero and the motor generates a random distributed torque. Based on the measured frequency response functions the parameters of the system are estimated with a linear least-squares algorithm. The identified parameters are: $m_{motor} = 0,33$ kg; $m_{slide} = 2,07$ kg; $k_{belt} = 7,96.10^5$ N/m; $k_{sensor} = 4,89.10^5$ N/m; $c_{motor} = 126$ Ns/m; $c_{belt} = 64,3$ Ns/m; $c_{slide} = 676$ Ns/m; $c_{sensor} = 0$.

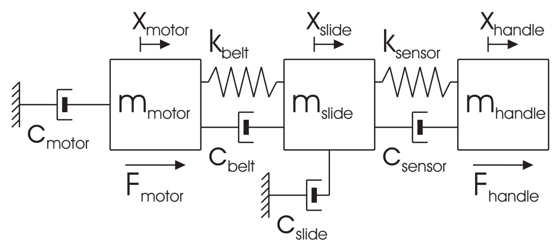

Fig. 3. The 6th-order model of the system

B. The position and admittance control loop

In the position control loop, the position of the motor shaft is fed back to a proportional controller. To decrease the overshoot of the position controller, negative speed feedback is used. The speed signal is obtained by filtering and differentiating the position signal. The allowable feedback gains are limited by saturation of the motor and by the poor quality of the speed signal. The feedback gain K_p of the position controller is set to a value of 15000 N/m and the feedback gain K_v of the speed feedback has a value of 200 Ns/m. In a second step, the measured force on the handle is used in the admittance controller to generate the damping behavior. The reference position for the position controller is obtained as $\int \frac{F_{handle}}{c_{adm}} dt$. When the operator is holding the handle, the system contains an additional feedback path. Depending on the impedance of the operator's arm $Z_{operator}$ and the set damping constant c_{adm}, this could lead to instability. Experiments identified that the maximal stiffness of the human arm is less than 5000 N/m. Using the identified dynamic parameters of the setup, simulations indicate that the damping constant has to be set higher than 100 Ns/m to guarantee stability.

In the next sections the developed control system, which is similar to prior work [2], [5], will be extended with new modules which estimate the transfer motion and generate the cooperative movement. The complete control system of the robot assistant is shown in figure 4.

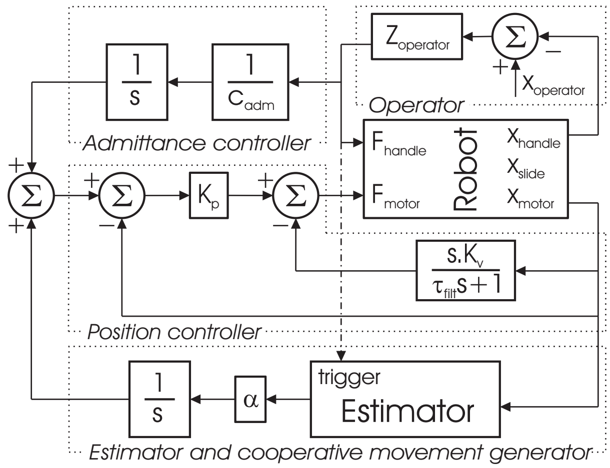

Fig. 4. The complete control scheme

IV. Assisting the operator with a going-along motion

Based on literature [6], it is likely that the assistance offered by the going-along motion will feel most natural to the human if this motion has a bell-shaped speed profile. However, before implementing the estimator which adapts the timing of the going-along motion to the intention of the operator, it is valuable to check this assumption. Besides the bell-shaped speed profile, a rectangular and a triangular speed profile are tested.

As described in the human-human cooperation, the interaction force on the handle triggers the start of the movement. As soon as the trigger is detected, the going-along motion is started. All three speed profiles are 0,5 seconds long and are tested with an increasing level of assistance of 0, 25, 50, 75 and 100%. Since the timing of the going-along motion is not adaptable, the operator is asked to adapt to the timing constraints imposed by the robot. For each setting, he can move the handle back and forth a few times, so he can adapt to the assistance offered by the system. During the experiment the admittance controller is active, allowing the operator to deviate from the going-along motion by exerting a force on the handle.

The results of the experiments where the level of assistance is equal to 75% are shown in figure 5. It is concluded by the operators that the rectangular speed profile does not feel natural because of the force impulse at the beginning and the end of the profile. They cannot adapt to this fast changing interaction. Although the triangular speed profile could be used for interaction, the operators report that the robot was doing something unnatural. With the bell-shaped speed profile however, most operators reported that it simply seemed as if the handle was becoming easier to move. The motion felt natural and human-like. Based on the feedback of the operators, it can therefore be concluded that the bell-shaped speed profile is the best choice for the going-along motion.

Figure 5.b shows that when the going-along motion has a triangular speed profile, the operator does not force the robot to move with a bell-shaped profile and the resulting speed profile of the handle becomes more or less triangular. This suggests that the operator is adapting to the assistance offered by the robot and supplies just enough energy 'to get the job done'. He prefers to move along with the speed profile in a kind of 'minimal-effort' way, instead of resisting it and forcing it to be a bell-shaped profile. However, when expecting pure damping forces, it feels strange to the operator that the interaction force falls back at high speed levels. Figure 5.c shows that when using the bell-shaped speed profile the speed and the reduced interaction force stay approximately proportional to each other. This gives the operator the impression that the damping coefficient c_{adm} is lowered and that the going-along motion is not there. This creates a feeling of natural interaction.

After the above stated experiments, in which the operator could gradually adapt to the set level of assistance, a second series of experiments were conducted. In these experiments the level of assistance was randomly varied, without informing the operator. For each setting, he had only one chance to move the handle. In these experiments, the interaction forces are much higher than in the first experiments, even for high levels of assistance. It can thus be concluded that the adaptation of the operator to the robot assistant is done between-trials and not during the execution of each movement. This is obvious because during the transfer motion the operator is moving the handle without thinking or modifying the trajectory. The experiments indicate that it is necessary to gradually increase the level of assistance for each operator. Only after this gradual increase the operator is able know how the robot will assist, which is necessary for safe interaction [4].

V. Estimating the going-along motion

In the previous experiments the going-along motion of the robot has a fixed speed profile. This restricts the possible co-operation between the robot and the operator to the execution of this predefined motion. To generalize the cooperation it is necessary that, during the execution of the motion, the robot adjusts its speed profile to the motion that the operator had in mind. This can be done by adapting the parameters of the bell-shaped speed profile. As shown in equations (1) to (4), the profile is defined by four parameters: t_0, y_0, Δt and Δy. In this paper, to reduce the complexity of the estimation, the start and goal positions y_0 and y_1 are marked on the linear slide and are considered to be known to the operator as well as to the robot assistant. The starting time of the movement is

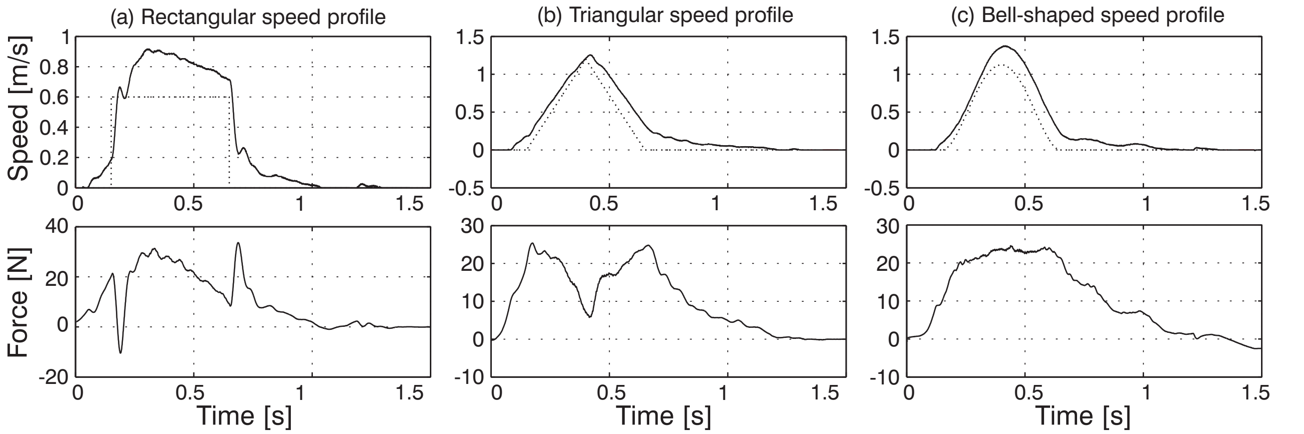

Fig. 5. Assisting the operator with a rectangular, triangular and bell-shaped speed profile with a level of assistance of 75%. (Solid line: measurements, dotted line: going-along motion)

identified by a trigger: at the time when the interaction force on the handle exceeds a threshold of 5 N, we obtain t_0. The remaining parameter Δt is estimated by a one-dimensional extended Kalman filter with the following characteristics:

- Only one state variable Δt. The estimate of Δt at time k is called $\hat{x}_k$.
- The process equation

$$x_k = x_{k-1} + \rho_p, \tag{5}$$

  where ρ_p is a noise term with zero mean and covariance Q.
- The position of the handle is assumed to be equal to the measured position of the motor. This measurement can be predicted out of the state by the non-linear measurement equation (cfr. equation (1))

$$z = \Delta y \ f\left(\frac{t - t_0}{x_k}\right) + y_0 + \rho_m, \tag{6}$$

  with t_0, y_0, Δy known parameters, t the current time, ρ_m a noise term with zero mean and covariance R and z equal to the measured position.

The specific equations which are necessary for the implementation of the extended Kalman filter can be derived out of these equations. For further details concerning Kalman filters, see [10].

Figure 6 shows the result of the estimation of the bell-shaped speed profile with measured data from a human motion. During this experiment the robot does not move along with the operator so he feels the interaction force with the admittance controller. The output of the estimation is the estimated Δt_{est} together with the current model-based speed v_{est} of a bell-shaped profile with parameters (t_0, y_0, Δt_{est}, Δy). This speed profile is not an exact bell-shaped profile, since the estimated Δt_{est} changes during the execution of the movement. The speed of the estimated motion profile will later be used as the speed of the going-along motion during cooperation between the robot and the operator.

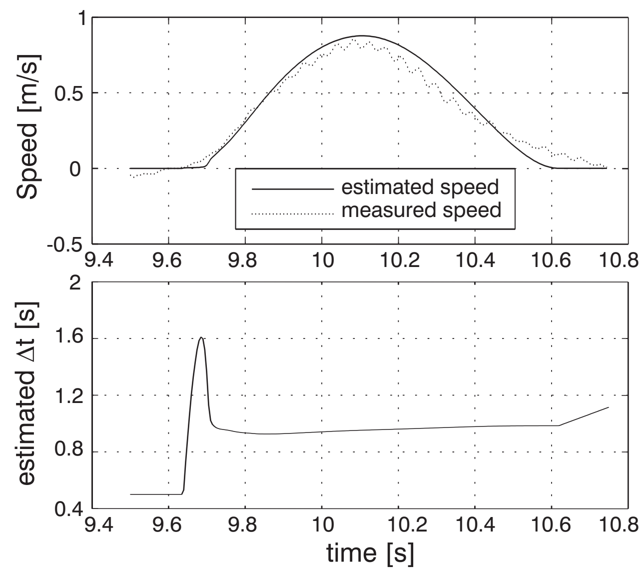

Fig. 6. Off-line estimation of the parameter Δt of the human motion profile and the resulting speed profile

VI. Evaluation of the human-robot cooperation

As explained in Section V, the applicability of a robot assistant which uses a preprogrammed speed profile is very limited. By using the previously designed estimator online, it is possible to offer assistance during a wider set of movements. The estimator will now continuously generate an updated v_{est}, resulting in a new set point for the reference input of the admittance controller on each time instant. This means that the going-along motion will adapt to the timing constraints the operator had in mind. However, as stated in section IV, the operator is also more or less adapting to the going-along motion of the robot. This chicken-and-egg problem could lead to problems, since it is practically impossible to prove the stability of this system.

Experimental validation revealed that the adaptation of the operator generates a kind of self-rectifying effect. This can

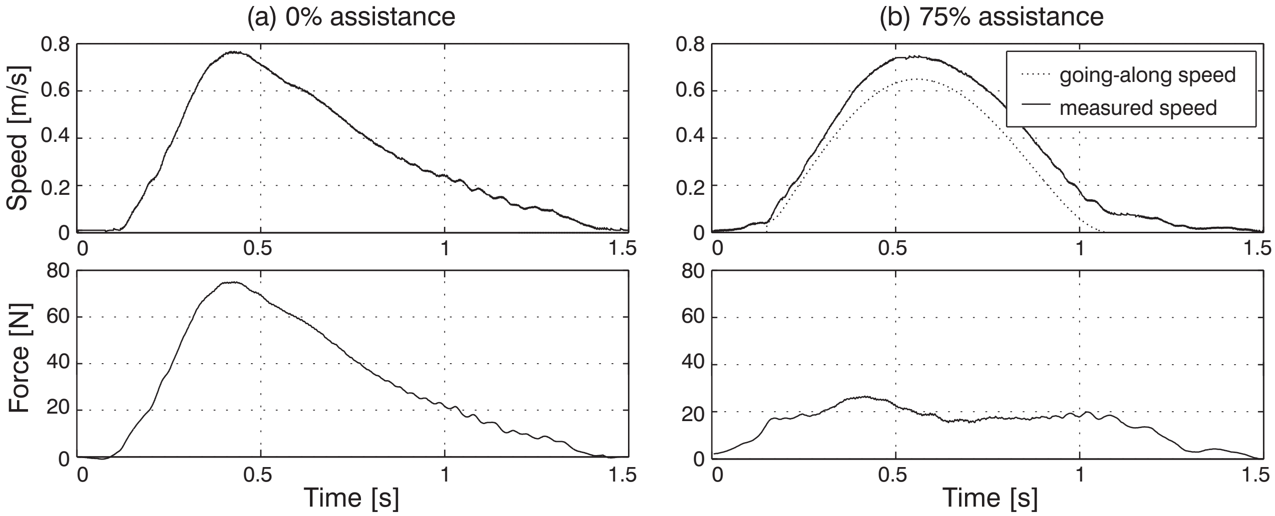

Fig. 7. A comparison between a point-to-point movement without assistance (a) and with a level of assistance of 75% (b).

be explained as follows: At the start of the movement, the operator has a certain speed profile in mind and executes this intended motion. At that time there is no going-along motion of the robot yet, and the operator feels the damping forces generated by the admittance controller. During this initial phase of the transfer motion, the estimated parameter of the speed profile Δt_{est} is close to the one the operator had in mind, but not completely equal. However, since the difference is acceptable to the operator he does not force the system to change the going-along motion. This confirms the estimated profile and at this point the operator's and the robot's intentions have converged. Figure 7 shows the results of an experiment with the online estimator. It can be seen that with a level of assistance of 75% (figure 7.b), the interaction force with the robot is greatly reduced compared to the same movement without assistance (figure 7.a). It is much easier for the operator to move the handle, while the speed and force profiles feel comfortable and natural.

It is important to note that during these experiments the level of assistance was gradually increased to give the operator the opportunity to adapt to the offered assistance. However, this adaptation was much faster than the one observed in section IV.

VII. Discussion and Conclusion

This paper provides experimental evidence that the active participation of the robot assistant during the execution of a point-to-point movement can greatly enhance the satisfaction of the operator. However, this evidence is only valid under the given conditions and has been gathered for a limited test group of approximately 10 people. A formal experimental procedure is required to prove the benefit of the approach. In addition, to use this technique in real-life applications, an extension to estimate spatial trajectories with an unknown target point is necessary. This extension is the subject of further research.

However, apart from these points, it is clearly shown that using models of human motion into the robot controller can improve the human-robot interaction. It feels natural to the operator that the robot is moving along using a bell-shaped speed profile, and since the admittance controller only contains damping the level of the offered assistance can be scaled. Especially in cases where, during fast movements, direct physical contact between the robot and the human is crucial, this approach can be useful to overcome the bandwidth limitations of the robot.

References

[1] J. E. Colgate, M. Peshkin, S. H. Klostermeyer, "Intelligent assist devices in industrial applications: A review", *Proc. Of the 2003 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems*, Las Vegas, Nevada, 2003, pp. 2516-2521.

[2] M.M. Rahman, R. Ikeura and K. Mizutani, "Investigating the impedance characteristics of human arm for development of robots to cooperate with human operators", *Proc. Of 1999 IEEE Int. Conf. on Systems, Man and Cybernetics*, Tokyo, Japan, 1999, pp. 676-681.

[3] Y. Maeda, T. Hara and T. Arai, "Cooperative human-robot handling of an object with motion estimation", *Journal of robotics and mechatronics*, Vol. 14, No. 5, 2002, pp. 432-438.

[4] J. Heinzmann, A. Zelinsky, "Quantitative safety guarantees for physical human-robot interaction", *The International Journal of Robotics Research*, Vol. 22, No. 7-8, July-August 2003, pp. 479-504

[5] T. Tsumugiwa, R. Yokogawa and K. Hara, "Variable impedance control with virtual stiffness for human-robot cooperative peg-in-hole task", *Proc. Of the 2002 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Lausanne, Switzerland, 2002, pp. 1075-1081.

[6] K. Ohta, M. M. Svinin Z. W. Luo and S. Hosoe, "On the trajectory formation of the human arm constrained by the external environment", *Proc. Of the 2003 IEEE int. conference on Robotics and Automation*, Taipei, Taiwan, 2003, pp. 2884-2891.

[7] J. E. Colgate, "The Control of Dynamically Interacting Systems", PhD Dissertation, Department of Mechanical Engineering, Massachusetts Institute of Technology, August 1988.

[8] N. Hogan, "Controlling impedance at the man/machine interface", *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, Scottsdale, USA, 1989, pp. 1626-1631.

[9] E. Burdet, T.E. Milner, "Quantization of human motions and learning of accurate movements", *Biological cybernetics*, No. 78, 1998, pp. 307-318.

[10] Y. Bar-Shalom and X. Li, *Estimation and Tracking, Principles, Techniques, and Software*, Artech House, 1993.