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Some Issues on Integrating Telepresence Technology into Industrial Robotic Assembly

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***Abstract*—**Since the 1940s, many promising telepresence research results have been obtained. However, telepresence technology still has not reached industrial usage. As human intelligence is necessary for successful execution of most manual assembly tasks, the ability of the human is hindered in some cases, such as the assembly of heavy parts of small/medium lots or prototypes. In such a case of manual assembly, the help of industrial robots is mandatory. The telepresence technology can be considered as a solution for performing assembly tasks, where the human intelligence and haptic sense are needed to identify and minimize the errors during an assembly process and a robot is needed to carry heavy parts. In this paper, preliminary steps to integrate the telepresence technology into industrial robot systems are introduced. The system described here combines both, the human haptic sense and the industrial robot capability to perform a manual assembly task remotely using a force feedback joystick. Mapping between the joystick's Degrees of Freedom (DOF) and the robot's ones are introduced. Simulation and experimental results are shown and future work is discussed.

***Keywords*—**Assembly, Force Feedback, Industrial Robot, Teleassembly, Telepresence.

I. Introduction

THE human haptic sense is an important aspect for numerous assembly processes, especially in manual assembly where 1) human intelligence is necessary for successful execution of given assembly tasks and 2) automation is costly [1]. In general, two error states can arise in assembly processes, namely lateral and angular (position and orientation) errors. These errors are responsible for generating forces and torques during assembly. In manual assembly, the human operator uses his haptic sense to identify what errors exist between the parts of the assembly and tries to react in a way that decreases these forces and torques, which means minimizing the errors and thus successfully performing the assembly process.

Although the assembly of small/medium lots can be carried out manually by a human operator, the help of robots in manual assembly is mandatory in some cases, where the ability of the human operator is hindered, such as the assembly of heavy parts.

The advantage of a robot in manual assembly systems is that some motions like gross motions can be automated, whereas the fine motion assembly processes are performed manually with the help of the human haptic sense. In this case, the system is called semi-automated robot assembly system. The question raised here is, how a human haptic sense can be appended to the manual or semi-automated robot assembly system.

The telepresence technology provides the possibility to combine the robot assembly and the human haptic sense in one system. In such a system, the robot hand is steered in response to the generated forces/torques which are sensed at the Tool Centre Point (TCP) of the robot and displayed to the human operator through a special haptic feedback device. Hence, the forces/torques sensed at the TCP are those generated by the assembly errors.

In general, telepresence systems consist of three parts: the human operator side, the robot side, and the communication link in between. At the human operator side, there is a force feedback joystick which displays the forces/torques sensed at the TCP of the robot to the human operator and receives the motion commands from the human operator and sends them to the robot side through the communication link. At the robot side, the robot performs the assembly tasks. The communication link between both sides shall retain the real time communication conditions between the haptic interface and the industrial robot to avoid synchronization and instability problems.

Following this introduction, this paper is organized as follows: The next section gives a description of teleassembly processes and previous work is mentioned. Afterwards, the system architecture of the proposed approach is explained. In section IV, the position/force bilateral control scheme is reviewed and motion control modes are then discussed in section V. The DOF mapping is introduced in section VI and some safety concepts are mentioned in section VII. Simulation and experimental results are presented in section VIII and IX. Finally, a conclusion and future work are given.

II. Teleassembly Processes

An assembly task is subdivided into two separate phases, gross and fine motions. Gross motions are fast and do not need high accuracy and are basically used for transporting the assembly parts to the mating position [2]. During gross

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motion, the robot moves unconstrained in the space to reach the mating position, so a conventional position control is suitable. Afterwards, the so-called fine motion assembly requires the capability of controlling both positions and contact forces with high accuracy [3].

The forces that arise in fine motion are usually due to glancing blows rather than head-on collision [2], and some motion usually continues along a deflected path. Two kinds of error can appear during fine motion: lateral and angular errors. Because of these errors, forces and torques are generated. These forces and torques can be used in a force feedback control strategy to minimize the assembly errors.

Some works have been done on the force feedback control to accomplish a successful automated assembly [4] and automated assembly in motion tasks [5]. Despite significant advances in the field of artificial intelligence [6], human intelligence is far superior in terms of reasoning, language comprehension, vision, and ingenuity, among others [7]. Some tasks may require both the acute reasoning and perceptive abilities of a human, and the strength and cooperation of a mobile manipulator. Therefore, it is necessary to design a control scheme such that humans may easily cooperate with a robot.

Since the simple peg-in-hole insertion (see Fig. 1) incorporates the features of a wide variety of simple assembly tasks, it has traditionally represented the benchmark of research in robotic assembly [8]. In this paper the simple peg-in-hole assembly is used as tele-assembly process. The tele-assembly process begins as the robot brings the peg into contact with the planar surface surrounding the opening of the hole. At that point, the human operator receives the contact force and generated torque through the force feedback joystick. The generated torque is due to the orientation error (the peg is not parallel to the insertion axis). The human operator will command the robot through the joystick to rotate the peg in the direction opposite to that generated torque in order to correct the orientation. After the orientation has been corrected, the human operator tries to move the robot laterally toward the hole keeping the contact between the peg and the surface by maintaining a constant contact force. Fig. 1 shows the phases of the fine motion during tele-assembly of the peg-in-hole scenario.

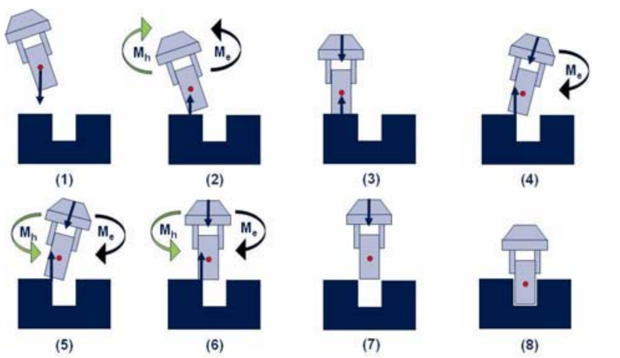

Fig. 1 Peg-in-hole assembly task. M_e and M_h are the **e**rror related and the **h**uman torque, respectively

III. System Architecture

Following the description of the tele-assembly process, the system setting is described. Fig. 2 shows the architecture of the industrial telepresence system, which consists of the human operator side, teleoperator side, central controller unit, and communication links in between. An experimental setup is shown in Fig. 7. The following sections describe each part in detail.

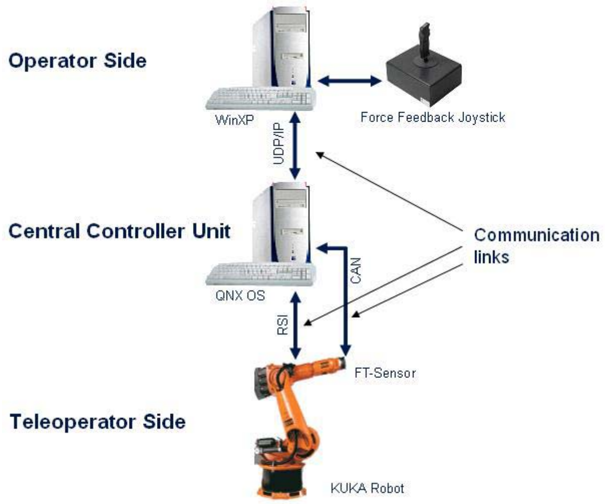

Fig. 2 System architecture

A. Operator Side

At the human operator side there is an input haptic interface device, which displays the forces/torques sensed at the TCP of the robot to the human operator and receives the motion commands from the human operator and sends them to the robot side via the communication link. In general, it is preferred to have a simple input device, in order to make it easier for the human operator to understand its movement. Therefore, a 2-DOF force feedback joystick is used in our system as an input device. This joystick can display a force up to 8.9N.

B. Teleoperator Side

The teleoperator side is where the robot performs the remote assembly tasks. The robot should have a force/torque-sensor mounted at the TCP to measure the interaction forces/torques generated during the assembly tasks execution. The KUKA industrial robot KR6 is used in our system as a teleoperator. It is a 6-DOF articulated industrial robot with a payload of 6 kg. The robot has a controller with a communication interface (Remote Sensor Interface) which is explained in the following subsection.

C. Central Bilateral Controller Unit

Between the operator and teleoperator sides the central bilateral controller is found. This controller described in section VII is implemented on a central controller unit and running on a real time operating system QNX, which guarantees a real time execution of the controller software.

D. Communication links

The force feedback joystick is connected to the central controller through a User Datagram Protocol (UDP) connection. Avoiding the overhead of checking whether every packet actually arrived makes UDP faster and more efficient than e.g. Transmission Control Protocol (TCP). Since our system is a time-sensitive system it is decided to use UDP, because dropped packets are preferable to delayed packets.

The KUKA.Ethernet Remote Sensor Interface (RSI) XML (Extensible Markup Language) is used to connect the teleoperator (KUKA robot) with the central controller. The exchanged data are transmitted via the Ethernet TCP/IP protocol as XML strings. The cyclical data transmission from the robot controller to the central controller is in the interpolation cycle of 12 milliseconds. This interface allows a direct intervention in the path planning of the robot during motion.

IV. Position/Force Bilateral Control Scheme

Fig. 3 shows the classical Position/Force bilateral impedance-based control scheme of a 1-DOF direct force reflecting teleoperation system using virtual coupling at the robot side. The following equations describe the dynamics of the system [9]

$$f_h^*(t) - f_h(t) = m_{op}\ddot{x}_m(t) + b_{op}\dot{x}_m(t) + k_{op}x_m(t) \quad (1)$$

$$f_h(t) - f_m(t) = m_m\ddot{x}_m(t) + b_m\dot{x}_m(t) \quad (2)$$

$$f_c(t) - f_e(t) = m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) \quad (3)$$

$$f_c(t) = B_c(\dot{x}_m(t) - \dot{x}_s(t)) + K_c(x_m(t) - x_s(t)) \quad (4)$$

$$f_e(t) = k_e x_s(t) \quad (5)$$

where
f_h^*: intentional contribution of the operator's hand
f_h: human operator's force
f_e: environment interaction force
f_c: slave controller computed force
x_m: master displacement
x_s: slave displacement
m_{op}, b_{op}, and k_{op}: human operator's inertia, damping, and stiffness, respectively
m_m and b_m: master manipulator mass and viscous coefficient
m_s and b_s: slave manipulator mass and viscous coefficient
k_e: environment stiffness (free movement case: $k_e = 0$)
B_c and K_c: slave controller parameters.

Transforming into the Laplace domain gives

$$F_h^*(s) - F_h(s) = \underbrace{\left(m_{op}s^2 + b_{op}s + k_{op}\right)}_{Z_{op}(s)} X_m(s) \quad (6)$$

$$F_h(s) - F_m(s) = \underbrace{\left(m_m s^2 + b_m s\right)}_{Z_m(s)} X_m(s) \quad (7)$$

$$F_c(s) - F_e(s) = \underbrace{\left(m_s s^2 + b_s s\right)}_{Z_s(s)} X_s(s) \quad (8)$$

$$F_c(s) = \underbrace{\left(B_c s + K_c\right)}_{Z_c(s)} \left(X_m(s) - X_s(s)\right) \quad (9)$$

$$F_e(s) = \underbrace{k_e}_{Z_e(s)} X_s(s) \quad (10)$$

where
Z_{op}: human operator impedance
Z_m: master device impedance
Z_s: slave robot impedance
Z_c: slave controller impedance
Z_e: environment impedance.

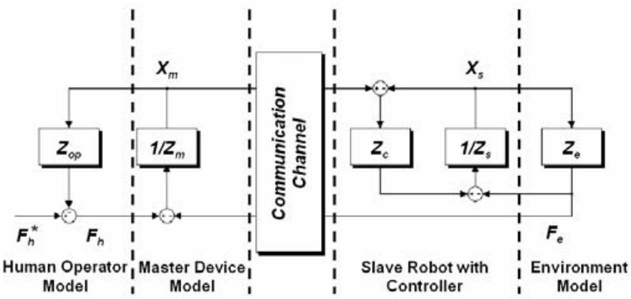

Fig. 3 A classical position/force bilateral control scheme of a teleoperation system [10]

V. Motion Control

There are two feasible control modes for steering the robot motion:

A. Position Control

Using the position control mode, the scaled joystick deflection is interpreted as an absolute desired position of the robot. This mode is proper for moving the robot within a limited workspace. Equation (11) describes this motion control mode.

$$(X, Y)_{rob} = K_p.(x, y)_{joy} \quad (11)$$

K_p here is the scaling factor. This factor is set to two values based on the kind of the motion, i.e. large value of this factor is suitable for gross motion, where no need for high accuracy and small value is suitable for fine motion, where the accuracy is very critical and the robot would come into contact with the assembly parts.

B. Rate Control

This control mode is used when the robot has a big or a non-limited workspace. In this project, the rate control is feasible just in the gross motion. Equation (12) describes the rate motion control. Here the scaled joystick deflection is interpreted as a time based increment of the robot, i.e. velocity of the robot.

$$(\Delta X, \Delta Y)_{rob} = K_V.(x, y)_{joy} \tag{12}$$

K_v is the scaling factor; i.e. a higher value results in a faster movement of the robot.

VI. Degrees of Freedom Mapping

The human operator moves the robot by manipulating the joystick. Since the joystick has two DOF, a mapping between these DOF and the six DOF (3 translational DOF and 3 rotational DOF) of the robot is needed. Our mapping strategy presented in this paper is to decouple the translational and rotational motions of the robot, i.e. to limit the motion to one mode at a time, either translational mode or rotational mode. This strategy makes it easier for the operator to understand the action of the joystick. The switching between these modes is done by means of a manual switch in the central controller interface.

A. *Translational Mapping*

There are three translational DOF. The two buttons of the joystick are used to switch between these DOF; i.e. the first 2-DOF (in xy-plane) and the third DOF (z direction) are enabled by the first and second button, respectively.

B. *Rotational Mapping*

When the human operator switches on the rotational mode, he can use the two buttons again to switch between the three rotational DOF; i.e. the rotations around x-axis and y-axis are enabled by the first button, while the rotation around the z-axis is enabled by the second button.

VII. Safety Concept

Since the system is going to have a direct contact with the human operator some safety concepts have to be considered, in order to make this interaction safe for the operator. The safety concept presented in this paper is divided into two aspects; the human opearator safety and the robot safety.

A. *Remote Presence of the Human Operator*

The human operator can manipulate the robot remotely by this system; i.e. he must not be present at the robot side. This allows having no direct physical interaction between the human operator and the robot. Although the human operator is not present physically at the robot side, he feels himself present at that side because he perceives all the sensory information from the robot side such as the visual, audio, and force feedback. Although there is a separation between the industrial robot and the human operator, the forces and torques exerted by the robot are fed back to the human operator through the force feedback joystick. In this case, the safety concept should consider this direct interaction between the human operator and the force feedback device.

Stiff-and-slow paradigm [11] is used to provide safe force feedback to the human operator; i.e. the controller is designed to slow down the robot as it becomes near to contact in order to feedback the forces of stiff contacts at low velocity, therefore supporting the safety of the overall system.

B. *Limited Workspace by means of Software Limiter and Force Feedback*

In the industrial telepresence system, the human operator is able to limit the workspace of the robot using a software limiter. By defining this limiter, the robot is not allowed to move outside this limited workspace. To give the human operator an indication that the robot is at the limit of the workspace, a force feedback is displayed to the human operator by the joystick. Fig. 4 shows the limited workspace and the direction of the forces as the robot reaches the boundaries.

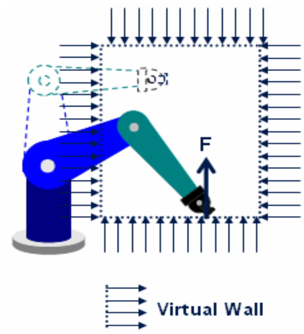

Fig. 4 Workspace limits

VIII. Simulation Results

In this section, the simulation results in MATLAB/SIMULINK of a simple lateral motion assembly are presented. During the simulation of the assembly task, generated forces are displayed to the human operator via the joystick.

The simulation system consists of the force feedback joystick, a virtual teleoperator model which is modeled as a virtual impedance-based 2-DOF manipulator (according to (10)) and a simple assembly task, which is modeled as an impedance-based virtual coupling at the teleoperator side based on (12). Fig. 5 shows the steps of the assembly task to be performed. The steps are: (a) approach along z-direction, (b) establish contact with the surrounding surface of the hole and sliding along x-direction toward the insertion position, (c) in front of the hole, where no force is fed back to the human operator, (d) insertion step along z-direction, and (e) assembly task is done.

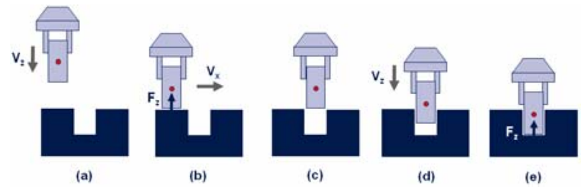

Fig. 5 Simulation scenario

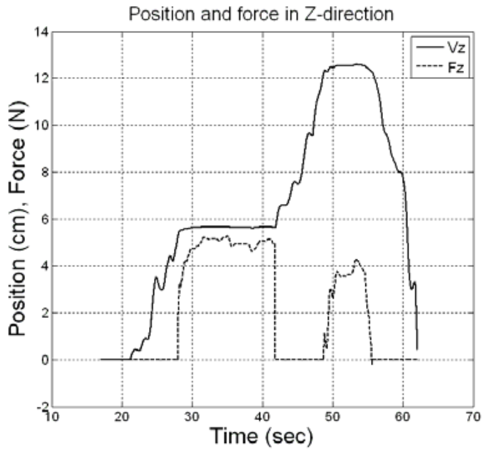

Fig. 6 Simulation results

Fig. 6 shows the position and generated force in one direction during the simulation of an insertion of a peg in a hole process. The approach phase (step 1) is between 20 s and 28 s. Hence the force is almost zero. At 28 s, the contact of the peg with the surface surrounding the hole is established (step 2) and a force is generated and displayed to the human operator through the force feedback joystick. When the peg is in front of the hole the force drops to zero and the human operator starts the insertion phase (step 3 at 42 s). The insertion phase is shown between 42 s and 49.5 s. Hence, no force is generated during this phase. As the peg is fully inserted a force is again generated and the human operator perceives a force which indicates the end of the assembly task (step 5 started at 49.5 s).

IX. Experimental Results

To validate the usability of the mapping strategy, some experiments are performed. The experimental setup of the industrial telepresence system is depicted in Fig. 7.

Fig. 7 Experimental setup

A. DOF Mapping Experiment

1) Translational Mapping

Fig. 8 shows the experimental results of the translational mapping between the force feedback joystick and the robot. The initial position of the joystick is (x=0,y=0), whereas the initial position of the robot is (x=1153,y=0,z=1010). After 4.9 s, the human operator switched from XY-movement to Z-movement. The X-direction of the joystick is then mapped to the Z-direction of the robot and the XY directions of the robot are constant and equal to the last values before the switching.

2) Rotational Mapping

To show the rotational mapping, some results are depicted in Fig. 9. Here, the movement of the joystick is mapped to rotate the TCP around the axes of the world coordinate of the robot. The initial position of the joystick is (x=0, y=0) and the initial orientation of the TCP is (around x: 0°, around y: 0°, around z: 0°). At the beginning the 2 DOF of the joystick are mapped to rotate the TCP around X- and Y-axis and after 7.9 s, the operator switched to rotate around Z-axis. For that, one DOF of the joystick is mapped to the angle of rotation around Z-axis.

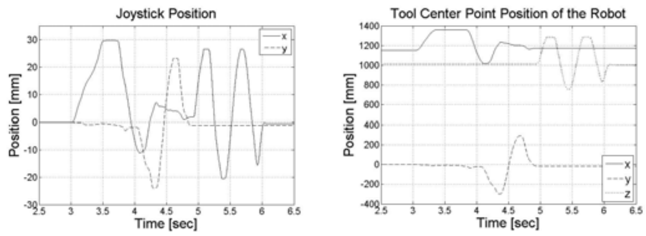

Fig. 8 Translational mapping: joystick position (left) and TCP position of the robot (right)

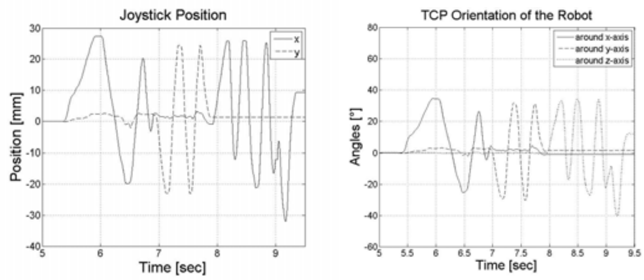

Fig. 9 Rotational mapping: joystick position (left) and TCP orientation of the robot (right)

From this experiment, it can be seen that the 2-DOF joystick can be used to move a robot with 6-DOF using the described mapping strategy. The advantage of having such a joystick is that it is very easy for the human operator to understand the joystick movement, comparing with other complex 6-DOF force feedback devices.

X. Conclusion

In this paper, the telepresence technology as a solution of bringing the human haptic sense into industrial robotic assembly system is introduced. The architecture of the telepresence industrial robotic system is presented. The use of a force feedback joystick to display the forces/torques generated during the assembly task to the human operator who controls the remote robot manually is discussed. The human operator uses the force feedback as an indication of the progress of the assembly task and reacts accordingly. The mapping between the 2-DOF joystick and robot with 6-DOF is shown. The advantage of having such a joystick is that it is very easy for the human operator to understand the joystick movement, comparing with other complex 6-DOF force feedback devices. Simulation results of an assembly task are shown. Experimental validation of the mapping strategy is provided. The work in this paper can be considered as a base to implement an industrial telepresence robotic assembly system using force feedback joysticks.

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