Experimental Evaluation of Feedback Modalities for Five Teleoperation Tasks

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Abstract—A distributed telerobotic system is proposed based on a master-arm station that is interconnected by a computer network to a slave-arm station. The distributed telerobotic system is evaluated using a set of teleoperated experiments: 1) peg-in-hole insertion; 2) assembly of a small water pump; 3) operating drawers; 4) pouring of water; and 5) wire wrapping. Direct teleoperation is evaluated using the following schemes: 1) stereo vision; 2) vision and force feedback (VFF); and 3) vision with active compliance (VAC). Space indexing and scaling tools are also used. Operator hand is logically mapped to a remote tool both in position and force. The operator feels the forces that were exerted on the tool as they were exerted on the hand. Extensive experimental analysis showed that mapping of operator hand motion and force feedback (FF) to a convenient tool point reduces the operator mental load and task time due to highly coordinated motion. Stereo vision may solely be used at the cost of large peak forces and extended task time. VFF has nearly equal task time compared to VAC but with a noticeable increase in contact forces. For a large majority of cases, the contact-based tasks that were done using VAC resulted in the least task times and the least contact forces. VAC is superior to VFF, which is better than V. In other words, there is an enormous gain in stability if one removes the bilateral FF channel in teleoperation and relies on a slave-arm active compliance.

Index Terms—Active compliance (AC), assembly, force feedback (FF), insertion, motion coordination, teleoperation, telerobotics, vision.

I. INTRODUCTION

TELEROBOTICS aims at extending human natural eye–hand motion coordination over an arbitrary distance and an arbitrary scale. The objective is to replicate manipulative skills and dexterity to a remote workplace. Human psychomotor skills have evolved over millions of years. The design of effective man–machine interfacing and the transmission delays are two major limiting factors [1].

A 3-D virtual reality (VR) model [2], [3] of the environment is used to develop model-based assistances and mixed control modes in repeatedly performing a sequence of short modeling, programming, and execution. A virtual arm is teleoperated, whereas accessibility is checked, valid paths are used to control the slave arm, and feedback from the slave arm is sent to control the virtual arm. The system is used in unfastening 12 nuts of a tap cover, lifting up a cover using a gantry crane, inspecting the tap, and lifting down the cover and fastening it again.

An event-driven VR [4] is used to model the environment to ease the task of programming, planning, and teleoperating a remote robot. Once the VR assemblies are set up, the real links update their recorded trajectory. This approach is useful in resolving conflicts among multiple robots while reducing communication bandwidth.

In [5], a sensor-based motion planning is proposed for teleoperation in deep space. Bilateral control of a graphic slave arm that operates on a 3-D graphic environment is used to select an approximate sequence of fine motions. The operator is provided with graphic animation using kinematics, dynamics, and friction. Impact forces that were used in a closed-loop control are used to provide the operator the feeling of repulsive forces. For this setup, a 3-D collision prevention scheme is used. The sequence is sent to a slave arm that is supervised by a sensor-based motion-planning algorithm and applied to a peg-in-hole assembly. Accurate graphic and physical models of the slave arm and the environment are needed.

Using a preplaned insertion path, adaptive impedance control [6] is used to reduce jamming forces by adaptively finding the desired position to follow the optimal path using the current position and environmental constraints. For peg-in-hole operations, the scheme may correct slight horizontal misalignment due to uncertainties. A two-level teleoperation scheme [7] is proposed for the wearable energetically autonomous robot. The master emits lower level commands using the natural intelligence of the operator. To make decisions for the management of the robot, artificial-intelligence-based commands blend higher level simple commands with the system and existing environmental states.

Bilateral control is one approach to replicate human performance at a remote site. Task performance can be improved when force reflection and shared compliant control are used but at the detriment of teleoperator stability. Theoretical analysis of stability/performance for position error based on Lawrence four- and five-channel schemes for teleoperation [9] indicated that a compliant slave device provides some stability.
advantage over a built-in passive intrinsic stiffness. Kinesthetic force feedback (FF) to the operator is helpful, even under a long delay [10]. A stable bilateral teleoperator was successfully used in carrying out peg-in-hole insertion (0.4-mm clearance) and contour following while exerting a constant force under a delay of 7 s. A gain-switching control [11] may improve the teleoperation transparency when using constant controller gains in position-error-based teleoperation during slavefree motion or when colliding with a stationary stiff environment.

An anthropomorphic space robot is evaluated using kinesthetic and stereo head-mounted display (HMD) [12]. The operator position is mapped to slave arm both in position and velocity. Evaluation of a drill task indicates less contact forces with equal task time when either visual or kinesthetic force is used with stereo vision (V). A mixed set of direct and task-oriented modes [13] are activated using a set of visualization and manipulation tools, with some force monitoring to improve safety and accuracy in microspaces or nanospaces. To avoid collisions, high-level motion commands are used due to electrostatic forces and possible sticking. For legged robots [14], the use of force sensing is useful to measure the foot-ground force interaction and the ground-reaction forces and to compute the zero-moment point in real time while standing or executing a dynamically balanced gait.

In surgery, force sensing is indispensable for a reliable perception of the stiffness of soft tissue [15] to discriminate tinier differences in telemanipulation with enhanced sensitivity than through direct manipulation. The use of FF during microsurgeries [16], [17] indicate that typical forces on the microsurgical instrument tips during the retinal surgery are less than 7.5 mN, which is below the threshold of the operator’s tactile sensitivity. Unless these contact forces are properly amplified, the surgeon will not sense them. Thus, the surgeon may operate with little or no tactile feedback, which increases the potential of tissue damage. To measure the contact forces, a miniature force sensor [16] is used at the tip of a microsurgical instrument. Position-controlled motion is proposed with micrometer resolution for FF of not less than 5 mN. The use of FF in remote endoscopic surgery [18] proved to be beneficial. The slave manipulator quickly and accurately mimics the movement of the master arm at low speed, and the master arm satisfactorily reproduced the force. FF [19] is also effective in suturing a rabbit’s neck artery (3 mm in diameter) and leg artery (1 mm in diameter).

A telerobotic framework is evaluated using direct teleoperation with the following schemes: 1) V; 2) vision and FF (VFF); and 3) vision with active compliance (VAC). Indexing and scaling tools are used. The proposed system is used to carry out a set of experiments that involve contact with the environment. Operator hand motion is mapped to a remote tool both in position and force. Strategies for task-effective execution are discussed and presented for the experiments. Analysis of operator interaction with the environment, task time, and peak and average contact forces is presented. Comments on the global performance of each scheme are presented together with a comparison to others.

This paper is organized as follows. In Section II, the telerobotic system is presented. In Section III, the description of experimental tasks is presented. In Section IV, the used tools and strategy for the experiments are presented. In Section V, the experimental results are presented. In Section VI, some results are compared to others. We conclude in Section VII.

II. TELEROBOTIC SYSTEM

Telerobotics allows extending eye–hand motion coordination through a computer network. Motion scaling establishes a mapping from the human scale to an arbitrary target teleoperation scale (e.g., microscale and nanoscale). Telerobotics is based on developing a multidisciplinary research environment that integrates motion, vision, and haptic senses to experience manipulative tasks, system interactions, man-machine interfacing, and computer-aided teleoperation (CAT). The fidelity in reproducing the tasks using different teleoperation schemes is assessed based on the analysis of some task performance metrics like peak and average contact forces and task time.

A schematic of our telerobotic system is shown in Fig. 1. The slave arm is a 6-DOF PUMA 560. The master arm (Pending U.S. Patent) is a light 6-DOF wire-based, anthropomorphic arm that was designed and manufactured at the King Fahd University of Petroleum and Minerals. The telerobotic system consists of a master-arm station that was organized as a telerobotic client (TC), which is interconnected through the Internet to a slave-arm station that was organized as a telerobotic server (TS). TC and TS implement the following three aspects: 1) bilateral master–slave interconnection at the Cartesian coordinate level; 2) motion coordination system and teleoperation tools; and
3) streaming of video data (V) and FF. The software architecture is described in [20].

In the following discussion, we shortly describe the generic impedance control that was implemented in the telerobotic system. At the slave arm, the joint control torque \( \tau \) is used to control the arm dynamics [21] as follows:

\[
\tau = M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) + J_s^T(\theta)F_{\text{ext}}
\]

where \( \theta, \dot{\theta}, \text{and} \ddot{\theta} \) are the slave-arm joint position, velocity, and acceleration, respectively, \( M(\theta) \) is the inertia matrix, \( C(\theta, \dot{\theta}) \) is the coriolis and centrifugal matrix, \( G(\theta) \) is the gravity vector, \( J_s(\theta) \) is the slave-arm Jacobian, and \( F_{\text{ext}} \) is the external force that was applied at the arm tip. The control torque \( \tau \) is computed as

\[
\tau = M(\theta)\ddot{q} + K_v\epsilon_0 + K_p\epsilon_\theta + G(\theta)
\]

where \( q \) is the master-arm joint position, \( \epsilon_\theta = q - \theta \) is the position error, and the diagonal gain matrices are \( K_v \) and \( K_p \). Note that \( M(\theta), C(\theta, \dot{\theta}), \) and \( G(\theta) \) are computed online by the controller. The closed-loop equation is obtained by combining the aforementioned two equations. We have

\[
e_\theta + K_v\epsilon_\theta + K_p\epsilon_\theta = M(\theta)^{-1}J_s^T(\theta)F_{\text{ext}}.
\]

The slave arm is controlled by the constant gains \( K_v \) and \( K_p \) independent of joint-dependent parameters such as inertia \( M(\theta) \), coriolis and centrifugal force \( C(\theta, \dot{\theta}) \), and gravity \( G(\theta) \).

The vector that represents the Cartesian variation in the operator hand position, and orientation is used to command the slave-arm tool frame (TF). In particular, the master-arm Cartesian velocity vector is computed as \( X_m = J_m(q)\dot{q} \), where \( J_m \) is the master-arm Jacobian matrix. For small variations \( \dot{q} \), we have \( \Delta X_m = J_m(q)\Delta q \). The variation vector \( \Delta X_m = (\Delta E_m, \Delta M_m) \) consists of a translational part \( \Delta E_m \) and a rotational (Euler) part \( \Delta M_m \), as shown in Fig. 1.

Cartesian mapping is implemented by controlling the slave arm using \( \Delta X_m \), for example, to eliminate the structural dependence between the master and slave arms. A desired joint vector \( q \) is computed for the slave arm as \( \epsilon_\theta = q - \theta = J_s^{-1}\Delta X_m \) and \( q = J_s^{-1}\Delta X_m + \theta \). The aforementioned terms allow for evaluating the control terms \( \dot{q}, \epsilon_\theta, \) and \( \epsilon_\theta \) that appear in (2).

Similarly, the master-arm motor torque vector \( \tau_m \) controls the dynamics [21] of the master-arm articulated system. We have

\[
\tau_m = D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q)
\]

where \( q \) is master-arm joint angular vector, \( D(q) \) is the inertia matrix, \( C(q, \dot{q}) \) is the coriolis and centrifugal coefficients, and \( G(q) \) is the gravity vector. This approach allows for computing the terms \( C(q, \dot{q}) \) and \( G(q) \) based on the dynamic model of the master arm. The inertia matrix \( D(q) \) is nearly constant for a light master arm that operates in a restricted work volume.

The force that was measured at the slave-arm tool will be displayed at the operator hand center. For this case, the master-arm controller computes the torque vector \( \tau_m \) as follows:

\[
\tau_m = \alpha\ddot{q} + \beta\dot{q} + C(q, \dot{q}) + G(q) + \tau_H
\]

where the term \( \alpha\ddot{q} + \beta\dot{q} \) is generated based on the operator motion, the terms \( C(q, \dot{q}) \) and \( G(q) \) are used to compensate for dynamic effects and gravity, and \( \tau_H \) is the reflected FF torque. Torque \( \tau_H \) is induced by the slave-arm force vector \( F_{\text{TF}} \), which is expressed in the TF but measured by a wrist force sensor, as shown in Fig. 2. In other words, \( \tau_H = \tau_{\text{ext}}^m = J_m^T(q)F_{\text{TF}} \). At the master station, \( F_{\text{TF}} \) is scaled (magnified) by the operator using the master arm as a pointer to some predefined scale in the stereo picture displayed on the HMD. More details about force conversion can be found in [22]. The overall dynamic motion equation becomes

\[
F_{\text{TF}} = J_m^{-1}(q)((\alpha - D(q))\ddot{q} + \beta\dot{q})
\]

where the term \( \alpha - D(q) \) represents the reduced master-arm inertia, and \( \beta\dot{q} \) is a damping factor. The motivation for injecting the term \( \alpha\ddot{q} + \beta\dot{q} \) in the master-arm torque is to reduce the overall mechanical impedance that the operator felt. The values of the parameters \( \alpha \) and \( \beta \) are experimentally determined. The aforementioned equation allows for displaying on the operator hand the force vector \( F_{\text{TF}} \) that was computed in the slave-arm TF.

In the following section, we present the experimentation details by considering the task description and specifications.

III. TASK DESCRIPTION AND SPECIFICATION

In this section, we describe the experimental part of a multithreaded distributed component framework for telerobotics. In the following sections, experiments are presented with their geometric and mechanical specifications.

A. Peg-in-Hole Insertion

The objective is to expose the proposed framework to an operation that involves the following aspects: 1) teleoperation with kinesthetic FF display at the master arm or with active compliance (AC) at the slave station; 2) logical mapping of operator hand motion to a floating TF attached to a peg;
3) the use of available CAT tools. Insertion deals with grasping of a peg, moving it to the top of a hole, detecting contact with the hole, and inserting the peg in the hole. The geometric dimensions, clearance, and chamfer geometry are shown in Fig. 3(a). For smooth insertion, the peg tip was rounded, and the hole was chamfered. To avoid damaging the robot and sensors, the hole was attached to a 1-kg base for which the sideways movements are permitted in response to a lateral force that exceeds 8 N.

B. Assembly of a Pump

This assembly requires a high degree of eye–hand motion coordination with balanced dependence on both vision and FF. In the studied case, the assembly operation requires two objectives that will be met at the same time. The mechanical tolerance of the parts is relatively moderate compared to that of the peg and the hole. These instances are shown in Fig. 3(b). A car water pump is used to carry out assembly and disassembly operations. The pump consists of three cylindrical parts: 1) a plastic cover (PC); 2) a metallic base (MB); and 3) a pump body (PB) that contains a motor that will be assembled in the middle of the aforementioned two parts. The motor shaft axis appears on both the top and bottom sides of the PB. Initially, the MB is attached to a fixed platform for which the sideway movements are permitted in response to a lateral force that exceeds 8 N. The MB can be tilted by up to an angle of 10° with respect to the horizontal plane. The task is to grasp the PB, move it to top side of the fixed MB, and carry out part mating of the PB and the MB. Then, the aforementioned operations are repeated to assemble the PC on the top of the PB–MB compound.

C. Operating Drawers

The task of operating drawers requires a high degree of eye–hand motion coordination with moderate use of FF. The drawer has a small vertical wing at its end to block its entire retrieval by only sliding it outward. Once it reaches the blocking position at its end, the removal of the drawer requires the following two steps: 1) tilting it upward to free its bottom; and 2) sliding it downward to free its top. Fig. 4(a) shows the specification of the drawer that was used.

D. Pouring

The objective is to expose the proposed framework to the following four aspects:
1) teleoperation with fine trajectory and time control;
2) extensive use of eye–hand motion coordination;
3) perception of 3-D scenes and scene depth;
4) evaluation of functional and ergonomic aspects of the proposed CAT tools.

This task deals with grasping of a small cup that contains colored water using the slave-arm gripper, moving it to the neighborhood of an empty cup, and pouring the water in the target cup (TC).

E. Wire-Wrapping Operations

The objective is to evaluate the performance of the proposed teleoperation system in a scaled-down slave-arm space. The task is to insert the head of the wire-wrapping tool (WWT) into a series of needles of a wire-wrapped electronic circuit. The operation must repeat from one needle to the next in a row of five. Fig. 4(b) shows the specification of the wire-wrapping gun and needles.

IV. EXPERIMENTAL METHODOLOGY

In this section, we describe the computing configuration prior to addressing the analysis of experimental results.

The TS and TC are run on two personal computers that run MS Windows 2000 and with 2-GHz Intel P4 processors with 1-GB DRAM and 512-KB cache memory. Programs are written in MS Visual C# with the above.NET framework. Each personal computer is attached to a campus network by
using a 100-Mb/s network interface controller card. The server personal computer is interfaced to two Sony Handycam digital cameras using a 400-Mb/s FireWire peripheral component interconnect card. The client personal computer uses an NVIDIA display adaptor to interface with a supervideo graphics array resolution Cy-visor 3-D HMD.

A sampling rate of 120 Hz is achieved for FF and 50 Hz for operator commands. Stereo video transfer operates at a rate of 17 fps. The total reference delays for force and stereo are 8 and 83 ms, respectively. Overall, the roundtrip system delay between the client and the server is 183 ms (5.5 Hz) when the slave arm is operated at 10 Hz, excluding delays that were caused by the operator. The aforementioned delays represent the “best effort” from the simultaneous streaming of video, commands, and force data over a campus network using MSF C# programming and .NET Remoting. The characterization of delays, delay jitter, and scattered distribution of video, commands, and force can be found in [22] and [23]. Video clips on these experiments can be found at [24].

In the next sections, the task strategy, experimental analysis, and results are presented.

A. Peg-in-Hole Insertion

Peg-in-hole insertion consists of searching an unconstrained motion path in a space that was constrained by the jamming force and moment (F/M). The peg is held by the slave-arm gripper. To start, the peg is held in the axial direction of the hole to the best of the operator and the V system. The displayed 6-D FF represents the forces that were exerted on the slave-arm tool to which the peg is firmly attached. Here, V perception provides coarse information, whereas displayed FF is critical to search unconstrained motion directions based on correcting both peg-in-hole axial and rotational mismatches.

Consider a mapping scheme (S1) for which the variation in the operator hand position and orientation is used to command the slave-arm attachment point (AP), as shown in Fig. 5(a). At the server, the force that was measured at the AP of the slave arm is computed and displayed, in the client station, at the operator hand center. Thus, the operator hand is mapped to the AP by both position and force. Here, V is not very helpful in making fine translational or rotational motion corrections. The operator hand is logically mapped to the peg at the AP; thus, a single F/M contact component corresponds to a subset of coupled F/M that are sensed by the operator at the AP, which might defeat the operator action to nullify the aforementioned F/M by simple hand motion. We found that it is difficult for a human to comprehend an F/M vector, which was applied to the hand, compared to a single F/M component. Therefore, setting the motion mapping should be guided by the need to uncouple the contact F/M in an attempt to reduce the operator mental load and operation time. For this mapping, S1 was abandoned due to the lack of efficiency.

Another mapping (S2) consists of initially setting the mapping point at the edge of the peg and dynamically computing the new mapping point by locating it in the middle of the peg part that is already inserted in the hole, as shown in Fig. 5(a), e.g., point TF. This scheme can be evaluated using the following two aspects: 1) the horizontal plane at the top of the hole, which is taken as reference for zero depth and 2) the current peg depth. This strategy aims at capturing the jamming F/Ms, where they are exerted on the peg, and displaying them on the operator hand to favor direct corrections of both peg-in-hole misalignment errors (moment) and translational errors (force). Hence, the objective of this mapping is to logically map the operator hand at a point where the following two conditions hold: 1) it is effective to capture the mechanical constraints such as the jamming forces and 2) it is easy to make necessary correction through motion mapping. The aforementioned point is dynamically remapped to the operator hand motion; thus, the operator rotational and translational corrections are likely to reduce the aforementioned constraints due to the one-to-one mapping of the jamming constraints and the corrective motion done by the operator. The scaling function is used here to scale down the operator motion in all directions to allow for the following two approaches: 1) fine motion correction in the horizontal plane and 2) controlling the force that was exerted by the peg on the hole. Visual monitoring is also used to appreciate the progress in the insertion.

Fig. 6(a) and (b) show the performance of the peg-in-hole insertion using the VFF and VAC teleoperation schemes. The upper and lower plots correspond to the displayed FF and operator motion command, respectively. These interactions are exchanged through the network. In Step 1 of the VFF, the operator searches an unconstrained motion path in a space that was constrained by a contact force (−4 N), e.g., a wall effect.
In Step 2, the operator changes direction and reduces lateral contact force, which allows the peg to go deeper in the hole. In Step 3, a different contact force appears, and the same cycle is repeated until completion of insertion.

The third approach (S3) consists of a supervisory corrective motion that was done by the local force controller and the remote slave arm. This solution is similar to the second mapping in terms of the measurement of mechanical constraints at the aforementioned floating TF point, but instead of forwarding the contact F/M to the operator, an AC controller is activated at the slave station (a shorter loop), which leads to superimposing locally computed peg motion corrections (i.e., rotational and axial corrections) to motion that was instructed by the operator. In this case, the operator may limit the control of the peg to the vertical direction with the corresponding FF. The space-scaling function is used here to scale down the operator motion in the horizontal plane (10 : 1) with a unit scale in the insertion direction, which allows the operator to control the vertical force that the peg is exerting on the hole.

In Fig. 6(b), AC control is set at the server. The upper and lower plots correspond to the displayed contact force, which is measured at the server, and the motion correction that the AC controller made, respectively. These interactions are local to the slave station. The operator applies a downward force (Step 1), whereas AC control searches a horizontal position and orientation (Step 2), which reduces contact F/M components. Due to the mapping of the tool F/M to the operator hand, components are likely to be uncoupled from each other and corrected independent of each other. This instance results in the lowest exposure to contact forces.

An experimental setting for a vision, FF, and AC (VFFAC) teleoperation scheme is shown for the case of the insertion in Fig. 7. VFFAC leads to excessive system instability, as shown by the large jamming force magnitude and interaction frequencies that were observed on the plot of the force compared to the interaction forces of the VFF and VCC schemes in Fig. 6. This excessive force magnitude is expected, because in VFFAC, there are two independent uncoordinated corrective processes: 1) the local AC and remote operator, which concurrently control the slave-arm tool, and 2) the delay time, i.e., the AC controller immediately reacts to the measured tool F/M, whereas the operator sees and feels the FF with the aforementioned delays. This case inevitably leads to some coupled corrections that destabilize the teleoperation system. Due to the aforementioned reasons, the VFFAC scheme is found to be not useful.

B. Assembly of a Water Pump

The assembly plan is given as follows. The PB is grasped and moved to the vicinity of the MB. The operator carries out axis alignment to the best of the available depth perception. The steps are shown in Fig. 5(b). Part mating requires meeting the following two constraints: 1) force contact of the motor shaft axis and insertion in the middle hole of the MB and 2) part mating of both lateral cylinders of PB and MB while maintaining axis alignment. The aforementioned constraints must be met in a sequential order, starting with the best possible configuration that can be achieved using V and later combining both FF and visual information. Similar operation is carried out to assemble the PC on the top of the PB–MB compound.
The assembly strategy consists of using a balanced mixing of visual and FF in addition to space scaling to maintain some geometric directions and keep correcting other references. In particular, visual feedback is used to establish a proper geometric setting in the prepositioning phase. The operator space mapping in the horizontal plane is scaled down, for example, by a factor of 10:1 to maintain the part positioning and to limit potential motion in the horizontal plane. The vertical axis is left with a unit scale under operator control. This approach allows for preserving axis alignment (first constraint) of the parts during the part-mating operation (second constraint). It allows the operator to carry out fine force control in pushing one part into another while monitoring the results. In the case of large positioning errors or axis misalignment during the part-mating operation, the tool is lightly lifted up (failure), and the space scaling is increased (e.g., to 3:1). Correction of part position and orientation are made before again attempting the part-mating phase. FF is critical in carrying out the part mating, in which the part is subject to a soft downward push under careful visual monitoring using zoomed V for the early detection of potential mismatch. In summary, successful part mating is based on a combination of fine FF control and depth perception in addition to the use of button-controlled tools like indexing and scaling.

Fig. 8(a) and (b) show the performance of assembly tasks schemes VFF and VAC, respectively. Under the VFF scheme, in Step 1, the PB is moved by the operator to the MB where a contact force is detected. Prepositioning and part mating are performed in Step 2. A sharp change in the displayed force causes a wall effect, e.g., resistance to motion. In Step 3, the PB is extracted from the assembly with a release FF and returns to zero force once in free air. The fluctuations in force are caused by the friction.

C. Operating Drawers

The drawer is pulled up until its top wing reaches the blocking point. During the aforementioned operation, motion scaling can be used to scale down the operator motion in all directions, except for the pulling direction to maintain directional motion. The blocking end is detected using both visual and FF.

To ease the task, the operator hand is mapped to a point TF of the MB. In Step 2, the PB is extracted from the assembly with an additional release FF and returns to zero force once in free air. The contact forces involved have less magnitude and duration than those of the VFF scheme.

![Strategy for operating a drawer and pouring water.](image-url)
projected on one single axis at the new location of the TF. In other words, the operator feels the contact between the wings with the environment as if the drawer is held by the operator. By tilting the hand in the upward direction, the front side of drawer is tilted up, which frees the drawer bottom that can now be shifted downward before becoming entirely free. During the aforementioned operations, the contact forces that were displayed on the operator hand (master arm) are very helpful in detecting potential contacts that may result from errors in the location of the TF and implied operator motion.

D. Pouring

The pouring operation consists of the following three approaches: 1) grasping; 2) traveling; and 3) pouring. Grasping requires the slave arm to move down to a preapprehension configuration prior to the grasping of a cup (FC) filled with colored water. The operator (in the loop) tries to center the jaw to the middle of the FC at its midpoint to avoid potential collision. During grasping, the indexing function is frequently used to maintain the master arm within a small operator dexterity area whenever the motion requires moving along a path with a long translation or rotation. Traveling requires lifting the FC and moving toward the TC while maintaining the slave gripper in a horizontal plane and progressively setting up of FC orientation when approaching the TC. Pouring requires setting up a proper prepouring configuration in the vicinity of the TC. Now, the FC must be tilted while keeping its top above the TC. This approach normally consists of a rotation and a translation, as shown in Fig. 9(b). To reduce the workload on the operator, it is more interesting to relocate the mapping function of the slave tool at one of the top lateral points of the TC, which becomes the origin of the new TF. In this case, tilting the operator hand leads to directly tilting the new TF about one axis of the aforementioned frame, as shown in Fig. 9(b). We note that placing the TF origin (and orientation) at the aforementioned critical point contributed in reducing the task time by about 40% compared to a default setting of the TF at a gripping point. In addition, it helped the operator in predicting the tool path occupancy during the hand-tool mapping. The aforementioned mapping provided an ergonomic teleoperation tool, because it helped in minimizing the number of iterations for setting the tool in a given configuration.

E. Wire-Wrapping Operations

The GUI is used to set up at the following two levels: 1) scale level of the FF and 2) the camera zooming level. Space scaling is directly controlled by the operator index. The converging setting consists of scaling the operator motion by a factor of 30:1, the FF by a factor of 1:10, and the stereo camera zooming by a factor of 1:40. The operator moves the WWT while aligning its axis with the circuit needle using V and carries out the insertion. The operator needs to feel the vertical force component to avoid damaging the needle during contact, because only a small central hole in the WWT must fit the needle, as shown in Fig. 4(b). In this case, the operator carries out corrections of axis misalignment and inserts the WWT's head in the needle. The distance between two needles is about 1.5 mm. The aforementioned task was successful in making five successive insertions in a line in 30 s. The operator adaptation to working with some small scale appeared to be smooth and simple. Multiple zooming views are useful to avoid changing the zooming level whenever axis alignment needs correction.

V. RESULTS AND DISCUSSION

In this section, we present the following two aspects: 1) the results of using the proposed telerobotic system in performing peg-in-hole insertion and assembly tasks and 2) recommendations on how man–machine interfacing can be improved. These tasks are selected, because they require effective interaction between the operator and the remote task that involves fine motion, FF, and V. The results are limited to the period of interactions with the environment, e.g., the insertion phase in the peg-in-hole operation and the part-mating phase in the assembly operation. Both phases follow the contact detection phase. We study the following teleoperation schemes in which the operator has control of a 6-DOF master arm and works with the aforementioned teleoperation schemes (i.e., V, VFF, and VAC).

Each of the insertion and part-mating phases was carried out by 12 students aged between 18 and 24. The designer explained to them the various aspects of the telerobotic system for 2 h. The objective function is to carry out the aforementioned two tasks in the least possible time while minimizing contact forces to reduce potential damage and improve teleoperation effectiveness. The objective function was carefully explained and discussed to the students. Each student was allowed to experience the insertion and assembly tasks at least ten times before recording the data. Thus, the initial learning period for each operator is between 1 and 2 h.

Each operator carried out the insertion and assembly tasks using the V, VFF, and VAC teleoperation schemes. Each scheme was carried out 12 times in total for each of the aforementioned two phases. The collected data refer to the maximum and average F/M magnitudes and the corresponding completion time of a given operation for a given operator. In total, we have 72 plots for two phases. The F/M vectors are all computed at the origin of reference TF. The F/M vector has six components; thus, each component contains qualitatively similar information in terms of the peak and average force and time dependence on the operator or AC controller corrections. Combined results for all operators are presented.

Figs. 10–13 show the maximum and average force that was exerted during peg-in-hole insertion and assembly versus task time, respectively. The operators were satisfied with the quality of V provided during the experiments. V is one critical augmentation in telerobotics. In general, the V scheme allows completion of the insertion but with the largest contact forces and completion times compared to the other schemes. Occasionally, the V scheme may produce less contact forces and possibly less duration than the other two schemes. Table I shows the ratio of the maximum and average force and task time for V and VFF over VAC. The use of only visual feedback for any operator makes it longer and harder to correct axis...
Fig. 10. Maximum insertion forces with the respective task times.

Fig. 11. Average insertion forces with the respective task times.

Fig. 12. Maximum assembly forces with the respective task times.

Fig. 13. Average assembly forces with the respective task times.

misalignment. Thus, the peak and average forces dominate in V compared to the other schemes, as shown in Table I. The average force indicated some dependence on the operator speed and overall performance for a given operator. The ranking of operator performance is mainly the same in each scheme.

With VFF, the operator is part of a force-position loop. The operator feels the contact F/M that was exerted on the remote slave tool and reacts by searching for a tool position and orientation that zeros the F/M. The average force magnitude and task time in Table I for both insertion and assembly indicate that VFF significantly contributed in reducing the contact forces throughout the task execution that were experienced under the V scheme.

On the other hand, VFF and V AC have comparable task times. However, VFF results in a noticeable increase in contact forces compared to V AC, as shown in Table I. The operator is part of the force-position loop under VFF; thus, delays cause some loop instability, which were shown in the FF component in Figs. 6(a) and 8(a). The instability contributes in degrading the overall teleoperation performance compared to a slave arm that implements a local AC, e.g., V AC. This case is shown in the FF component in Figs. 6(b) and 8(b) and by the ratio V FF/V AC in Table I. For a large majority of cases, the contact-based tasks that were carried out using V AC resulted in the least contact forces and least task times. One may conclude that the active-compliance loop at the server station is better prepared to react to contact forces than the remote operator. This case shows the efficiency of the supervisory approach and its local AC that continuously searches to nullify the external F/M by correcting tool position and orientation at the current TF. Occasionally, V AC gets higher times due to temporary blocking that was caused by excessive vertical force commanded by the operator.

Referring to Table I, teleoperation with V AC is still ranked first but with less advantages in the assembly, as shown for the average force and task time. The reason is probably due to the operator’s ability to combine FF with vision perception in the critical phases of part mating. In both insertion and assembly, V AC contributed in reducing the peak and average contact forces compared to both the V and V FF schemes, particularly in the case of the insertion. V AC equally reduced the task time for each of the V FF and V schemes in both insertion and assembly tasks.
Some of the major sources of fatigue are given as follows: 1) the difficulty of comprehending and interpreting 6-D vector F/M and 2) eyes stress that was caused by the extensive use of V. Operators comfortably worked between 1 and 2 h with an acceptable level of fatigue.

Telerobotics needs advanced supervisory tools that embed complex force and position control with dynamic motion/force mapping. Effective man–machine interfacing is needed to integrate the aforementioned tools in a simple natural way at the operator index and stereo space. The stereo space that is visible to the operator and its AR capabilities need to support the aforementioned integration. The connectivity between the master and slave arms can temporarily be switched off, and the master arm can be used as a 3-D pointer. A variety of AC scenarios can be associated graphical features in the operator stereo space. These features can be selected and grouped in AC compounds (ACCs) as task-oriented and operator-favored tools. To activate a specific ACC at the task point of interest, the operator can use the master arm to point to a given ACC in the stereo space, drag it, change its orientation, drop it at a desired tool point, and control its activation. This approach allows for composing optimized ACC mechanisms and efficiently activating them at the right location and orientation with respect to the current task.

VI. COMPARISON TO OTHER SCHEMES

In VR-based teleoperation [2]–[4], [13], the operator plans an operation using a model, the plan controls a slave arm, and the slave arm transmits back parametric feedback. The primary issue is operation safety. Offline approaches are mainly used, and teleoperation is carried out on a static environment with no dynamic interaction reported. However, in [5], graphic animation of robot kinematics, dynamics, friction, and impact forces in a closed-loop control provides the operator the feeling of repulsive forces, which allowed the operator to carry out peg-in-hole insertion. The proposed telerobotic framework provides direct-oriented teleoperation with CAT tools that were augmented with some supervisory control schemes to improve teleoperation effectiveness in real interactions with the environment.

We concur with [10] on the importance of kinesthetic FF in assembly operations. We extended direct teleoperation by using compliance control that makes the slave arm continuously searching to nullify the F/M that was sensed on the current tool, whereas the whole arm is being driven by the operator to take advantage of the aforementioned mechanism in the current task. In comparison to [6], our proposed VFF and VAC schemes have similar effects in modifying the task trajectory. The AC controller continuously produces corrections in tool position and orientation that reduce tool external F/M. The operator sets task-oriented compliance and leads the arm under compliance equilibrium to work location. The proposed VAC scheme reduced peak contact forces and task time compared to kinesthetic FF with vision in insertion and assembly tasks. VAC may also be useful as a task locality mechanism to ensure task continuity in delayed teleoperations. We use constant controller gains in the dynamic controller for which the gain-switching technique in [11] may improve sensitivity and transparency, particularly in the case of contact with rigid, elastic, or tissue objects.

The wrench mapping in [12] is comparable to the proposed tool motion and force mapping. However, our dynamic mapping scheme proved to be a useful tool for several tasks where the point of interest is a function of the task state. The proposed mapping makes the operator logically mapped, in position and force, to the remote object. In addition, we proposed indexing and scaling tools and a tool-oriented dynamic motion mapping in position and force to carry out coordinated motion as a strategy for reducing operator cognitive load. This approach enables force reflection from the current tool to the operator, which increases the feeling of telepresence and enables teleoperation tasks to more easily be completed and with lower contact forces. The accomplishment of the aforementioned experiments is fundamentally due to the proposed dynamic mapping scheme, which is estimated to be the most critical CAT tool in the proposed telerobotics.

We presented extensive experimental analysis that shows that VAC is superior to VFF, which is better than V. Note the gain in stability, which is observed in Figs. 6 and 8 when switching from VFF to VAC. There is an enormous gain in stability if one removes the bilateral FF channel in teleoperation and relies on a slave-arm AC.

VII. CONCLUSION

A set of assembly tasks have been used to evaluate a client–server telerobotic system that transfers motion, FF, and V over a network. The tasks are given as follows: 1) peg-in-hole insertion; 2) assembly of a pump; 3) operating drawers; 4) pouring of water; and 5) wire wrapping. The operator has been provided with the following features: 1) V; 2) VFF; and 3) VAC. AC has been used as an aid to direct teleoperation in addition to indexing and scaling tools. A dynamic mapping of operator hand motion and force to a task-oriented tool point has been used to reduce operator cognitive load and task time. Button-controlled indexing and scaling proved to be the most frequently used tools. Scaling was useful for operating in a 30 : 1 scaled-down space and a linear dimension blocking tool. The V scheme allowed for completing the aforementioned tasks but resulted in the largest contact forces and task times compared to VFF and VAC. In contact-centric tasks, e.g., insertion, VAC noticeably outperforms V and VFF and provides task quality control. In multobjective tasks, e.g., assembly, VAC and VFF are closer in the peak and average force and in task times. However, the VFF results depend more on operator skills. There is an enormous gain in stability if one removes the bilateral FF channel in teleoperation and relies on a slave-arm AC. Teleoperation modality with VAC control is useful for extending human eye–hand motion coordination and dexterity to a remote workplace in hazardous, hostile, unaccessible, and small-scale environments.

REFERENCES


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