Qualitative Evaluation of Computer-Aided Teleopearation

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***Abstract*— Computer-aided teleoperation (CAT) is investigated for extending human eye-hand motion coordination and dexterity. A telerobotic system consisting of a master arm and a slave arm interconnected by a computer network is designed. The proposed system is evaluated using a set of experiments which are (1) operating drawers, (2) pouring of water, and (3) wire-wrapping. The non deterministic behavior of force contact favor a qualitative evaluation of teleoperation methodology. Direct teleoperation is evaluated using following schemes: (1) direct bilateral master-slave (DBMS) with stereo vision, (2) DBMS with vision and force feedback, and (3) BDMS with vision and active compliance. CAT tools used are space indexing, scalability, and selective scalability (blocking). Stereo vision is critical resource for teleoperation even with highly coordinated tool motion but it is not efficient alone to avoid excessive contact force and to shorten task time. Slave compliance continuously searches to nullify the external forces by correcting the tool position and orientation based on measured contact force. Space indexing is essential to maintain tele-operation in operator dexterity. Selective scalability is frequently used to linearly block some motion directions while keeping other directions under direct operator control. Mapping of operator hand motion and force to a dynamically computed tool point proved to reduce operator's cognitive load and task time and ease of understanding of force feedback. This greatly reduces the number of task iterations because the tool DOFs become decoupled, i.e. varying one likely not to affect the others.**

***Index Terms*— Computer-aided telerobotics, force feedback, indexing, motion coordination, scalability, stereo vision.**

I. Introduction

TELEROBOTICS allows replicating operator hand manual skills and dexterity to a remote work-scene based on real-time interaction with the environment using visual and haptic feedbacks. Human psychomotor skills have evolved over billion of years which explain the difficulty in designing a high-fidelity telepresence system. The two major limiting factors seem to be the lack of an effective man-machine interfacing and the transmission delays.

CAT tools greatly enhance teleoperation but heir management increases the user cognitive load in equipment inspection procedures [1], [2]. Computer graphics and virtual reality are used to rapidly acquire a geometric 3D model of the environment based on its utilization. Teleoperation is enhanced using model-based assistances and mixed control modes in repeatedly performing a sequence of short modeling, programming, and execution. In the case of exceptions new assistances are planned and the model is updated using new views. A virtual arm is teleoperated to set up a goal and a 3D path, accessibility is checked, valid paths control the slave arm, and as feedback the virtual arm reports the actual slave arm motion. The system is used in inspection procedures like unfastening of 12 nuts of a tap cover, lifting up a cover using gantry crane, inspecting the tap, and lifting down the cover and fasten it again.

Adaptive Impedance control (AIC) [3] at the slave arm is proposed as a shared-control strategy for teleoperation. For peg-in-hole operations, the scheme may correct slight horizontal misalignment due to uncertainties and part dimensioning tolerances. Using a pre-planed insertion path, AIC reduces jamming forces by finding the desired position adaptively to follow the optimal path from the current position, where the optimal path is updated based on environmental constraints. The AIC is more effective than traditional impedance control in reducing axis misalignment.

In [4] a generalized bilateral control (cartesian) based telerobotic system is proposed to augment teleoperation with scaling, indexing, and impedance control, shared control, and the use of an independent-structure master arm. The scheme reduces contact forces by scaling the space and force reflection by setting up soft stiffness at the slave arm and large damping at the master arm.

To reduce the operating load such as end-effector, payload, gravity, and damping cause by force feedback a Cartesian mapping [5] is proposed instead of a joint-to- mapping. This allows carrying out a task wrench with reduced contact wrenches. The method is also useful for kinesthetic haptic display in virtual or simulated environments. The remotely-sensed task wrench or computer generated virtual task wrench can be sent to the active hand controller to let the user feels the tasks wrench. The hand controller has man-machine has bottoms for (1) wrench reflection mapping, (2) force reflecting reference pose and indexing, and (3) wrench reflection. Wrench-reflection to the operator promotes lower contact wrenches. The amount of work in peg-in-hole insertion is reduced to about one third than without force information.

A micro/nano space is operated using a task oriented teleoperation system [6]. A mixed of direct and task oriented modes are activated using a set of visualization and manipulation tools with some force monitoring. Direct teleoperation is not recommended to avoid collision among robot and world. Teleoperation is done using high-level motion commands with

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terminal conditions. The approach is faster and safer with higher accuracy than direct teleoperation given the presence of dominant electrostatic forces and possible sticking of handling tool.

In [7] a sensor-based motion-planning is proposed for teleoperation of unexpected events in deep space. A bilateral control is used between a master arm and a graphic slave arm operating on a 3D graphic environment to select an approximate sequence of fine motions. Graphic animation of robot kinematics, dynamics, friction, and impact forces used in a closed loop control provides the operator the feeling of repulsive forces. A 3D collision prevention scheme is used. The sequence is sent to a slave arm supervised by a sensor-based motion-planning algorithm under impedance control where it is accurately coordinated in a real-time assembly tasks. The method is successfully applied to peg-in-hole assembly. This approach needs accurate graphic and physical models of slave arm and environment.

In this paper a distributed telerobotic framework that consists of a client (operator) and a server (slave arm) stations interconnected by a network. Operator uses Head-Mounted Display (HMD) to provide 3D perception of remote workspace. A set of computer-aided teleoperation CAT tools are developed and experimental evaluated by using a set of real-life experiments. The tools are engineered with objective to improve teleoperation efficiency and ergonomics, reduce task time, and ease man-machine interfacing. The paper reports qualitative conclusions on the proposed CAT tools as experienced in specific teleoperation tasks.

The organization of this paper is as follows. In Section 2 telerobotic system overview is presented experimental tasks are presented. In Section 3 used tools and strategy for the above experiments are presented. In Section 5 the global experimental results are presented. In Section 6 obtained results are compared to other contributions. We conclude in Section 7.

II. A MULTI-THREADED DISTRIBUTED FRAMEWORK

The aim is to extend natural eye-hand motion coordination through a computer network while preserving human manipulative dexterity in scaled working environments. The objective is to develop a multi-disciplinary telerobotic research environment integrating motion, vision, and haptic senses to experience telerobotic system interactions, man-machine interfacing, and computer aided teleoperation (CAT).

A schematic of the proposed *Multi-Threaded Distributed Framework* (MTDF) is shown on Figure 1. The server station has (1) a slave arm module that consists of a PUMA (S_{PUMA}) and a Force (S_F) components, and (2) a video (S_V) component. The client station has (1) a master arm component that consists of a Motion (C_M) and a Force (C_F) components, and (2) a video component (C_V). All client (server) components are concurrently run as independent threads on the client (server) computer. Real-time thread S_V (S_F, C_M) is logically interconnected to C_V (C_F, S_{PUMA}) to which it sends data through the network. In the following we present the implementation of each of the client and server sub-systems.

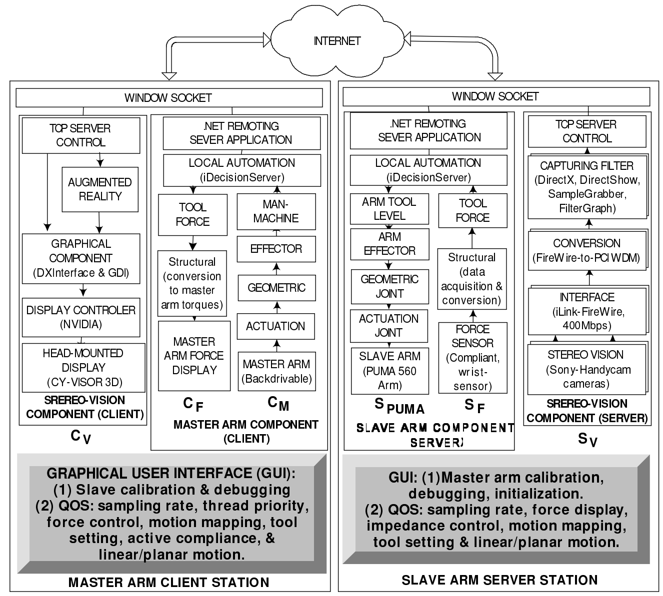

Fig. 1. A layered schematic of the telerobotic system

The MTDF is based on is based on the implementation of a client and a server components that are reliably connected by stereo, force, and commands data streams through a network. The multi-threaded aspects stem from the simultaneous client and server threads. Server threads simultaneously carry out grabbing of stereo video data, reading force sensors, sending control signals to the robot, reading the feedback from the robot servo controller, and sending and receiving all of the above information to one or more clients. The client threads simultaneously (1) grabbing of position data, performing impedance control, and displaying of force feedback on master arm, (3) display stereo images on client 3D visualization system, and (2) transmitting to server differential master arm position through the network. The distributed approach leads the logic of the system be distributed in different software components.

A. System overview

The Telerobotic system is started by running the server program At the slave arm station to provide (1) a connection to the PUMA slave arm, (2) a graphical user interface (GUI) for maintenance and debugging of slave arm, and (3) the server function which consists of listening to the network for any client requesting a connection. At the client station, the client program (1) requests a network connection with server station, (2) generates a GUI for maintenance issues. The client GUI allows setting up the priority, and execution rates of various processes (threads) at both the client and server which allows some generic quality of service set up.

The operator is holding the handle of a light, 6 DOF, wire-based, anthropomorphic, master arm that was designed in our Robotics Lab, King Fahd University of Petroleum and Minerals. Some of the CAT functions can be activated using buttons disposed on the master arm handle to ease control of the system and to avoid distracting the user attention. The

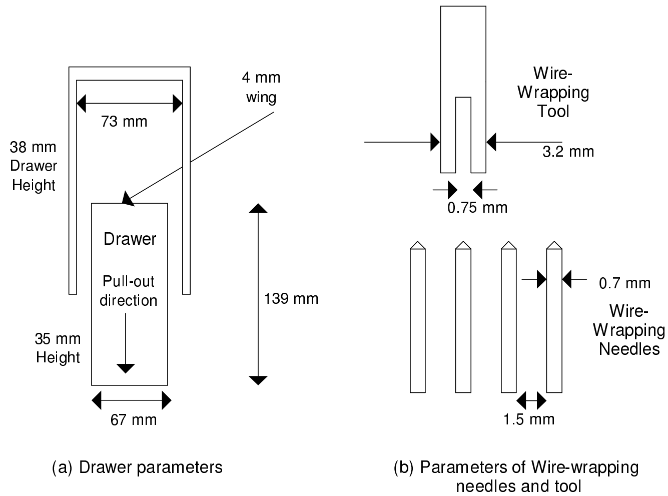

Fig. 2. Dimensioning parameters of drawers and wire-wrapping experiments

CAT functions are (1) arm indexing, (2) space scalability, (3) tool frame definition using AR functionality, and (4) selection of motion mapping. Motion mapping refer to the mapping of operator hand motion to a specific frame of the slave arm, i.e. world, wrist, or tool frame.

The master arm is used to display on the user a stream of reflected force feedback originated from the slave arm tool frame. In addition the user wears a head-mounted display (HMD) that receives live stereo video frames (17 stereo fps) originated from two cameras pointing to the workspace at the slave station. The user hand motion is mapped to a defaults too frame. In other words, the sensed force at the slave arm is computed with respect to the current tool frame before being transmitted to client station and displayed on the user hand. The above client and server setting are valid for all the experiments described in this part.

III. Task description and specification

In this section we describe some of the experimental part of a multi-threaded distributed component framework for telerobotics [8] and [9]. In the following sub-sections experiments are presented with their geometric and mechanical specifications.

A. Operating drawers

The task of operating drawers requires a high-degree of eye-hand motion coordination with moderate use of force feedback. The used 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 (1) tilting it upward to free its bottom, and (2) sliding it downward to free its top. Figures 2-(a) shows the specification of the drawer used.

B. Pouring

The objective is to expose the proposed framework to the following aspects: (1) teleoperation with fine trajectory and

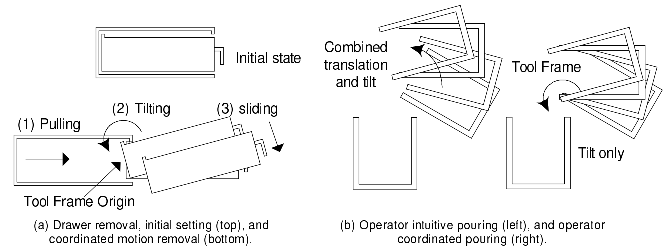

Fig. 3. Strategy used for operating a drawer and pouring water

time control, (2) extensive use of eye-hand motion coordination, (3) perception of 3D scene and scene depth, (4) evaluation of functional and ergonomic aspects of 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.

C. The wire-wrapping operations

The objective is to evaluate performance of proposed tel-operation system in a scaled-down slave arm space. The task is to insert the head of the wire-wrapping tool into a series of needles of a wire-wrapped electronic circuit. The operation must repeat from one needle to next in a row of 5. Figures 2-(b) shows the specification of the wire-wrapping gun and needles.

IV. Experimental methodology

In this section each task will be analyzed with respect to tools used during its teleoperation, methodologies used to ease its achievement, and obtained results. Video clips on this task are available at [10]. In the following subsections the strategy and analysis of carrying out each of the tasks are presented.

A. Operating drawers

The drawer is pulled up until its bottom wing reaches the blocking point. During the above operation motion scalability can be used to scale down the operator motion in all directions except the pulling direction to maintain directional motion. The blocking end is detected using both visual and force feedback.

To ease the operator task TF must be located at end of the drawer so that the needed tilt operation can be made using a rotation about the horizontal axis of TF. Figure 3-(a) shows the initial closed drawer (up) and the steps for its opening and entire removal (down). For this, the GUI, AR tools, and master arm are used to point to the new TF origin O_{TF}. This allows relocating TF. Now the operator hand motion maps logically to TF and the contact F/Ms are now computed with respect to TF before being forwarded to the operator or locally used in the slave active compliance loop. This provides one of the best possible logical mapping from the operator hand to manipulated object so that the needed action is projected on one single axis at the new location of 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 above operations the displayed contact forces are very helpful in detecting potential contacts that may result from errors in the location of TF and implied operator motion.

B. Pouring

The pouring operation consists of (1) grasping, (2) traveling, and (3) pouring. Grasping requires the slave arm to move down to a pre-apprehension configuration prior to grasping of a cup (FC) filled with colored water. This is done while continuously trying to center the jaw to middle of FC at its mid height 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 consisting of a long translation or rotation. Traveling requires lifting FC and moving towards the target cup (TC) while maintaining the slave gripper in a horizontal plan and progressive setting up of FC orientation when approaching TC. Pouring requires setting up a proper pre-pouring configuration in the vicinity of TC. Now FC must be tilted while keeping its top above TC. This normally consists of a rotation and a translation as shown in the left part of Figure 3-(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 point of 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 above frame as shown in the right part of Figure 3-(b). We note that placing TF origin (and orientation) at the above critical point contributed in reducing the task time by about 40% as compared to default setting of TF at gripping point. In addition, it produces a predictable trajectory while being an ergonomic teleoperation tool.

C. The wire-wrapping operations

The GUI is used to set up (1) scale level of force feedback, and (3) the camera zooming level. The 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 force feedback by a factor of 1:10, and stereo camera zooming by a factor of 1:40. The operator moves the wire-wrapping tool (WWT) while aligning its axis with the circuit needle using 3D vision and carries out the insertion. The operator needs to feel the vertical force component to avoid damaging the needle during contact because actually only a small central hole in WWT must fit the needle as shown on Figure 2-(b). In this case the operator carries out corrections of axis mis-alignment, and (2) insert WWT head in the needle. The distance between two needles is about 1.5 mm. The above task was successful in making five successive insertions in a line in 30 seconds. The operator adaptation to teleoperation to small scale appeared to be smooth and simple. Multiple zooming views is useful to avoid changing the zooming level whenever axis alignment needs correction.

V. Results and Discussion

In this section we present the global results of using the proposed telerobotic system in performing the above teleoperation tasks, the CAT tools developed to support teleoperation, and recommendations on how to improve the man-machine interfacing telerobotics. We study the following teleoperation schemes in which the operator has control of a 6 DOF master arm and provided with (1) only 3D visual feedback (V), (2) 6 DOF kinesthetic force feedback with 3D visual feedback VFF, and (3) visual feedback with active compliance VAC operating at the slave site. The non deterministic contact forces during each experiment favor a qualitative evaluation.

A. CAT tools

We present observations on the computer-aided teleoperation tools used in performing the above tasks which are (1) space indexing, and (2) space scalability. Space indexing is a critical CAt tool that allows the operator to maintain his arm in his dexterity area while freezing the mapping with remote slave arm at each indexing operation. The indexing function is activated using a push-button on the hand controller to avoid distracting the operator attention. In all of the above tasks the indexing function is the most frequently used among all CAT tools. A few indexing operations allows (1) setting up the slave arm in the most appropriate geometric configuration for the task, and (2) the operator hand is set in the most dexterous position and orientation. Although we used an anthropomorphic master arm, all operators preferred working in a small but dexterous hand-controller space formed by a sphere of about 40 cm diameter.

Another critical CAT tool is the scalability function which maps the operator motion (position) and force feedback to a scaled slave workspace with proper control of camera zooming level. The scale is controlled by a a finger-controlled linear input set up on the hand-controller. This allows the operator to operate a workspace of a few millimeters while providing bidirectional conversion of the position and force that exchanged between the two spaces. The operator-hand position and orientation are scaled by a user-controlled bottom. On the other hand force the reflected force feedback measured at the current tool frame origin is also scaled by the reciprocal scale factor. Convergence of the left and right HMD images when zooming above 1:60 requires the camera directional axes to have equal angle with the horizontal plan to eliminate any degradation of HMD stereo vision due to tilted cameras. This allows successfully accomplish the wire-wrapping task by providing linear scale mapping that is adapted by the operator to the workspace scale. In addition a selective scale function has also been implemented. Based on above experiments, selective scalability, without camera zooming, was frequently used to linearly block some motion directions to maintain their position and/or orientation while keeping other directions under operator control with unit scale. Planar (2D) or linear motion (1D) blocking consists of constraining some tool motion axes to linear or planar motion and leaving the other axes under direct operator manual control. Blocking of some tool position directions and orientation angles proved to be useful to teleoperate a restricted number of dofs in some delicate tasks like operating the drawers and insertion. Selective scalability is frequently used in complex task phases. For example, after setting proper drawer orientation the operator blocks (scale-down) of lateral drawer motion before the pulling phase.

B. Motion coordination

The operator has buttons to activate a set of assistance functions which are: (1) Relative or world mapping, (2) Floating tool mapping, and (3) Planar or linear motion. In the relative or world mapping, the operator motion is mapped to: (1) world frame in pre-positioning phases to set up proper pre-task position and orientation, or (2) incremental tool frame mapping to logically map the tool to hand-controller origin. In the floating tool mapping, the operator motion is dynamically mapped to the slave tool frame by recomputing the tool frame position and orientation based on task progress at some tool point of interest. For example, highly coordinated motion is achieved in the pouring task when the tool point is set at the one side of the cup as opposed to being at the cup origin. In inserting the drawer, the tool origin is computed at the center of the drawer part that is already inserted. This greatly reduces the number of iterations done by the operator to accomplish the task as the three linear motion axes and the three correction angles become decoupled due to the dynamic tool mapping, i.e. varying one likely not to affect the others which significantly reduces the number of iterations to accomplish the task.

Mapping of operator hand motion and force to a floating tool point proved to reduce operator's cognitive load and task time due to highly-coordinated motion and ease of force understanding. Operator is logically manipulating the remote object both in motion and force and feels the exerted forces as they were exerted in his hand. The operator can focus on the remote task without paying attention to his arm or the master arm. The HMD makes it impossible for the operator to see his hand. The proposed motion mapping was effective in all the tasks. Setting up the position and orientation of tool frame is based on temporally using the master arm as a 3D pointer in the stereo space. In the insertion, pouring, and drawer operating tasks the motion mapping were one of the very useful factors in proposed telerobotic system.

C. Direct and supervisory telerobotics

Operating the drawers was carried out by 12 operators, each carried out successively schemes V, VFF, and VAC. Each scheme was carried out 12 times in total for each of the above two phases. Each operator was allowed to experience the task at least 10 times before recording the data. The operators are aware of the need to minimize contact forces to reduce potential damage and improve operation effectiveness. The collected data refers to maximum and average F/M magnitudes as well as the corresponding completion time of a given operation for a given operator. The system is sampled at 50 Hz on slave arm station. The local compliance is a mechanism implemented at the slave arm (server) that continuously searches to nullify the external F/M by correcting the tool position and orientation at current task frame.

The operators were satisfied with the quality of stereo vision provided during the experiments. Scheme V allows completion of the task but with the largest contact forces and completion times as compared to VFF and VAC. It may produce less contact forces and possibly less duration than the other two schemes. However, the use of only visual feedback for any operator indicates that another critical feedback is missing due to excessive contact forces (drawers) exhibited during the contact task. The average force indicated some dependence on the operator speed and overall performance for a given operator. The ranking of any given operator performance is mainly the same in each scheme.

For a given user, teleoperation with vision and active compliance VAC always outperforms the V (vision) and VFF (vision with force feedback) but with less deviations in the magnitude of the contact force. VAC allowed carrying out the task with the least task times and contact force. V allows completion of the task but nearly doubling or tripling the contact forces and doubling the task time as compared to VAC. Teleoperation with VFF slightly increases task time but with a noticeable increase in contact forces as compared to VAC. VFF produces the largest variation in time from one operator to another. This shows that active compliance loop at the server station is better prepared to correct contact forces than the remote human which is an indication of the efficiency of supervisory approach and its local compliance. that continuously searches to nullify the external F/M by correcting tool position and orientation at current TF. Occasionally VAC gets higher times due to temporary blocking caused by excessive vertical force commanded by the operator.

For tasks involving contact with the environment, teleoperation with VAC is always ranked first but with more or less less advantages depending on the effectiveness of the vision is speeding up the task. The reason is due to the operator ability in some tasks to combine force feedback with 3D perception in the critical task phase, a feature that only the operator can perform.

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 above tools in a simple and natural way at the operator index and stereo space. The stereo space visible to the operator and its AR capabilities need to support the above integration. The connectivity between master and slave arms can be temporarily switched off and master arm used as a 3D pointer. A variety of active compliance (AC) scenarios can be associated graphical features in the operator stereo space. These can be selected and grouped in AC compounds (CACs) as task-oriented and operator favored tools. To activate a specific CAC at the task point of interest, the operator can point to a given CAC in stereo space, drag it, change its orientation, drop it at a desired tool point, and control its activation. This allows composing optimized AC mechanisms and efficiently activating them at the right location and orientation with respect current task.

VI. COMPARISON TO OTHERS

In virtual reality based teleoperation [1], [2], [11], [6] the operator plans operation using a model, the plan is used to control a slave arm, and slave arm transmits back parametric feedback to master station. The primary issue is planning for operation safety during inspection procedures. Mainly off-line approaches are used. They require modeling of geometric and dynamic features and are limited to static scenes because off-line analysis of contact force feedback requires complex knowledge of object geometry, dynamic, and material. Teleoperation on a static geometric environment with no dynamic interaction is reported.

In [12] a direct bilateral teleoperation (DBT) system is used to show that kinesthetic force feedback is very useful even with a round trip delay of 6 seconds. Inserting an 18 mm peg in a hole with 0.4 mm clearance proved that kinesthetic force feedback is very useful even with large delays. In comparison to [3] the proposed VFF an VAC schemes have similar features in modifying operator trajectory. The slave arm AC controller continuously searches corrections in tool position and orientation that reduce tool external force and moment. Operator sets task-oriented AC and leads the arm under compliance equilibrium to work location. AC reduced peak contact forces and task time as compared to force feedback with stereo vision peg-in-hole insertion and assembly of a pump. AC may augment force feedback in delayed teleoperation.

As compared to [4] the proposed system also uses indexing and scale in addition to a tool-oriented dynamic motion mapping in position and force to carry out highly coordinated motion as a strategy to reduce operator mental load. This enables force reflection from current tool to the operator which increases the feeling of telepresence and enables teleoperation tasks to be completed more easily and with lower contact forces.

The wrench mapping of [5] is comparable to proposed floating tool motion mapping that dynamically computes new tool in a task-oriented set up. To augment teleoperation with task-oriented active compliance we proposed a man-machine interface based graphical AC features. Using operator stereo space, AC graphical features can be selected and grouped in a compound AC (CAC) that matches the current task needs. Operator can point CAC, drag it, change its orientation, and drop it at desired tool motion coordination point. The result is an effective man-machine interface to compose complex AC mechanism and activates it at the right location and orientation.

VII. CONCLUSION

A set of tasks has been used to evaluate a client-server telerobotic system which transfers motion, force feedback, and stereo vision over a network. Used CAT tools consists of (1) space indexing, (2) space scalability, and (3) dynamic mapping of hand motion and force to a task-oriented tool point. The teleoperation tasks are (1) operating drawers, (2) pouring of water, and (3) wire-wrapping. Used teleoperation scenarios are (1) direct bilateral master slave (DBMS) with stereo vision V, (2) DBMS with vision and force feedback VFF, and (3) DBMS with vision and active compliance VAC. Active compliance is has been used as assistance to direct teleoperation in addition. Stereo vision alone allowed to complete the above tasks but resulted in the largest contact forces and task times. Active compliance noticeably reduces force magnitude and task times. Force feedback produced variable performance as it depends more on operator skills. Button-controlled indexing and scalability proved to be the most frequently used tools. Scalability was useful to operate in a 30:1 scaled down space as well as a linear dimension blocking tool. Force feedback and active compliance are critical tools for extending human eye-hand motion coordination and dexterity to remote work in hazardous, hostile, un-accessible, and small-scale environments. For future development, a graphical tool is proposed for composing compliance mechanisms that can be dragged, attached to a tool point, and activated to ease man-machine interfacing.

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