Evaluation of Assembly Tasks in Augmented Telerobotics

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***Abstract*— A distributed telerobotic system consists of a client station (operator) and a server station (slave arm) interconnected by a computer network. The system is evaluated using (1) peg-in-hole insertion, and (2) assembly of a small water pump. Direct teleoperation is evaluated using following schemes: (1) stereo vision, (2) vision and force feedback, and (3) vision with active compliance. Space indexing and scalability tools are also used. Mapping of operator hand motion and force feedback to a convenient tool point reduces operator mental load and task time due to highly-coordinated motion and ease of understanding of force feedback. Operator is logically manipulating the remote tool both in motion and force and feels the exerted forces as they were exerted in the hand. With active compliance all tasks are done in the least task times and with the least contact force. Stereo vision may alone be used but with large peak forces and extended task time. Force feedback has nearly equal task time as compared to active compliance but with a noticeable increase in contact forces. Force feedback and active compliance are critical tools for extending human eye-hand motion coordination and dexterity to remote work in hazardous, hostile, inaccessible, and small-scale environments.**

***Index Terms*— Active compliance, assembly, force feedback, insertion, motion coordination, stereo vision, teleoperation.**

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 work place.

A 3D virtual reality model [1], [2] of the environment is used to develop model-based assistances and mixed control modes in repeatedly performing a sequence of short modelling, programming, and execution. The system is used in unfastening 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.

An event-driven virtual reality (VR) [3] 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 placed, the real links update their recorded trajectory. In [4] a sensor-based motion-planning is proposed for teleoperation in deep space. Bilateral control of a graphic slave arm operating on a 3D graphic environment is used to select an approximate sequence of fine motions. The sequence is sent to a slave arm supervised by a sensor-based motion-planning algorithm and applied to peg-in-hole assembly. Using a pre-planed insertion path, adaptive impedance control (AIC) [5] is used to reduce insertion jamming forces by finding the desired position adaptively to follow the optimal path from the current position and environmental constraints.

To reduce teleoperation payload, gravity, and damping cause by force feedback a Cartesian mapping [6] is proposed. 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.

In this paper a telerobotic framework is evaluated using direct teleoperation with following schemes: (1) stereo vision, (2) vision and force feedback, and (3) vision with active compliance. Indexing and scalability tools are used. Operator hand motion is mapped scheme to remote tool both in position and force. Strategy for task effective execution is presented for each experiment. 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 is presented together with a comparison to other contributions.

The organization of this paper is as follows. In Section 2 used tools and strategy for the above experiments are presented. In Section 3 the global experimental results are presented. In Section 4 obtained results are compared to other contributions. We conclude in Section 5.

II. Experimental methodology

In this section the strategy and analysis of carrying out the insertion and assembly tasks are presented. Video clips are available at [7].

A. Peg-in-hole insertion

The peg-in-hole insertion consists of searching an unconstrained motion path in a space constrained by the jamming F/M. The peg is held by the slave arm gripper. The geometric dimensions, clearance, and chamfer geometry are shown on Figure 1-(a). To start, the peg is held in the axial direction of the hole to the best of operator and the 3D vision system. The displayed 6D force feedback represents the forces exerted on the slave arm tool to which the peg is firmly attached. Here 3D vision perception provides coarse information while displayed force feedback is critical to search unconstrained motion directions based on correcting both peg-hole axial and rotational mismatches.

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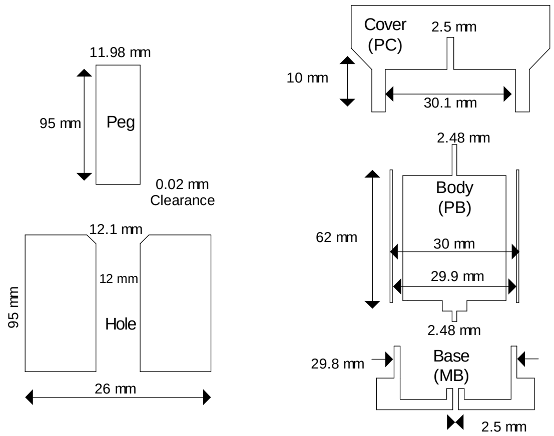
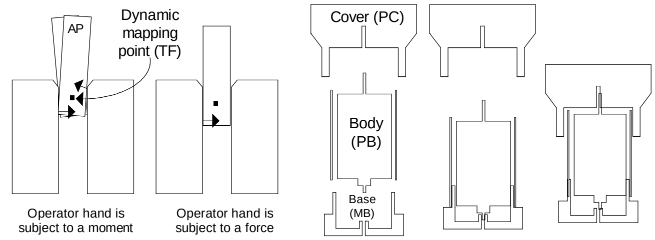


(a) Peg-in-hole parameters and chamfer geometry

(b) Assembly part parameters and clearences.

Fig. 1. Features and parameters of the peg-in-hole and pump components



(a) Contact force/moment and tool frame location for coordinated teleoperation.

(b) Assembly parts (left), base-body sub-component (mid), and base-body-cover assembly (right).

Fig. 2. Strategy used for peg-in-hole insertion and assembly of a water pump.

Using the operator-arm interface, a static mapping (S-1) is to link the operator hand to the arm-peg (AP) attachment point. At the server, this mapping also enables computing the external force and moment (F/M) in a frame of reference centered at AP. At the client, the computed external force is displayed at the operator hand using the master arm. Here the stereo vision is not very helpful in making fine translational or rotational motion corrections. Since the operator hand is logically mapped to the peg at point AP, a single F/M contact component corresponds to a subset of coupled F/M being sensed by the operator at AP which might defeat the operator action to nullify above F/M by simple hand motion. We found that it is difficult for a human to comprehend an F/M compound, applied to hand, as opposed to a single F/M component. Therefore setting the motion mapping should be guided by the need to uncouple contact F/M in an attempt to reduce the operator mental load and operation time. For this mapping S-1 was abandoned due to lack of efficiency.

Another mapping (S-2) consists of initially setting the mapping point at the edge of the peg and dynamically compute the new mapping point by locating it in the middle of peg part that is already inserted in the hole as shown on Figure 2-(a). This can be evaluated using (1) the horizontal plan at the top of the hole which is taken as reference for zero depth and (2) current peg depth. This strategy aims at capturing the jamming F/Ms where they are exerted on the peg and display them on the operator hand to favor direct corrections of both peg-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 it is: (1) effective to capture the mechanical constraints such as the jamming forces, and (2) easy to make necessary correction through motion mapping. Since the above point is dynamically re-mapped to the operator hand motion, thus, the operator rotational and translational corrections are likely to reduce the above constraints due to the one-to-one mapping of the jamming constraints and the corrective motion done by the operator. The scalability function is used here to scale-down the operator motion in all directions to allow fine (1) motion correction in the horizontal plan, and (2) position control of the force exerted by the peg on the hole. Visual monitoring is also used to appreciate the progress in the insertion.

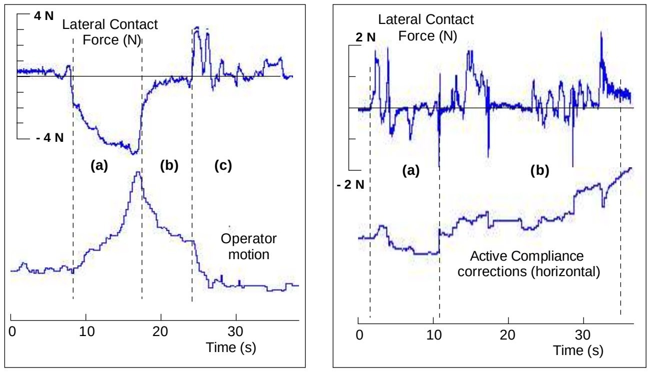
Figures 3-(a) and (b) show performance of peg-in-hole insertion using teleoperation with stereo vision and (1) force feedback (VFF), or (2) active compliance (VAC). The upper and lower plots correspond to displayed force feedback and operator motion command, respectively. These interactions are exchanged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

The third approach (S-3) consists of a supervisory corrective motion done by the local force regulation and the remote slave arm. This solution is similar to the second mapping in terms of measurement of mechanical constraints at the above floating TF but instead of forwarding contact F/M to the operator, active compliance controller is activated at the slave station (shorter loop) which leads to superimpose locally computed peg motion corrections (rotational and axial corrections) to motion instructed by the operator. In this case the operator may limit his control of the peg to vertical direction with the corresponding force feedback. The space scalability function is used here to scale-down the operator motion in the horizontal plan (10:1) with a unit scale in the insertion direction which allows the operator to control the vertical force the peg is exerting on the hole.

In Figure 3-(b) an active compliance control is set at the server. The upper and lower plots correspond to displayed contact force measured at the server and the motion correction made by active compliance controller, respectively. These interactions are local to the slave station. The operator applies a downward force (step (a)) while active compliance control searches a horizontal position and orientation (step (b)) that reduces contact F/M components. Due to proper mapping, F/M components are likely to be uncoupled from each other and corrected independently from each other. This results in the lowest exposure to contact forces.

B. Assembly of a water pump

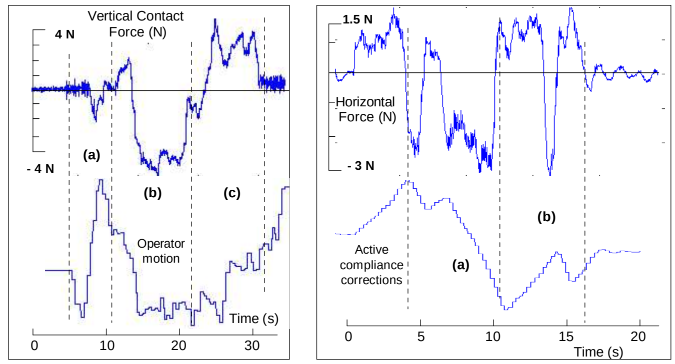
The assembly plan is as follows. PB is grasped and moved to the vicinity of MB. Operator carries out axis alignment to



Insertion using Force Feedback VFF:
(a) motion in direction of constraints, (b) avoid constraint and zero force, and (c) searching to nullify force in opposite direction.

Insertion using Active Compliance VAC:
(a) approaching hole and contact, (b) insertion attempts, progress in depth, and contact with hole bottom.

Fig. 3. Insertion using force feedback (a) and active compliance (b).



Assembly using force feedback VFF:
(a) approaching pump-base and contact, (b) part mating of body and base, and (c) removal of body.

Assembly using active compliance VAC:
(a) corrections made by AC while operator push downward for part mating, (b) operator removes body and reaction of AC.

Fig. 4. Assembly using force feedback (a) and active compliance (b).

the best of the available 3D depth perception. Part tolerance and geometry are shown on Figure 1-(b). The steps are shown on Figure 2-(b). Part mating requires meeting two constraints which are (1) force contact of the motor shaft axis and insertion in the middle hole of MB, and (2) part mating of both lateral cylinders of PB and MB while maintaining axes alignment. The above constraints must be met in a sequential order starting with the best possible configuration that can be achieved using 3D stereo vision and later combining both force feedback and visual information. Similar operation is carried out for assembling PC on the top on PB-MB compound.

The assembly strategy consists of using a balanced mixing of visual and force feedback in addition to space scalability to maintain some geometric directions and keep correcting other references. Specifically the visual feedback is used to establish a proper geometric setting in the pre-positioning phase. The operator space mapping in the horizontal plan is scaled down, for example by a factor of 10:1, to maintain the part positioning and to limit potential motion in the horizontal plan. The vertical axis is left with unit scale under operator control. This approach allows preserving axis alignment (first constraint) of the parts during the part mating operation (second constraint). It allows the operator exerting 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 scalability is increased (for example to 3:1). Correction of part position and orientation are made before attempting again the part mating phase. Force feedback is critical in carrying out the part mating in which the part is subject to a soft down-ward push under careful visual monitoring using zoomed stereo vision for the early detection of potential mismatch. In summary, successful part mating is based on a combination of fine force feedback and 3D depth perception in addition button-controlled tools like indexing and scalability.

Figures 4-(a) and (b) show performance of assembly tasks schemes VFF and VAC, respectively. Under VFF scheme, in step (a) PB is moved by the operator to MB where a contact force is detected. Pre-positioning and part mating are performed in step (b). Notice the force feedback (wall effect) displayed on the operator. In step (c) PB is extracted from the assembly with a release force feedback and return to zero force once in free air. The fluctuations in force are caused by the friction.

In Figure 4-(b) the sensed contact force is used by the active compliance to carry out corrections of position and orientation of PB while the operator attempts the part mating. Part mating is performed in step (a). Notice the resulting force feedback when the part hits the bottom of MB. In step (b) PB is extracted from the assembly with an additional release force feedback and return to zero force once in free air. The contact forces involved have less magnitude and time than those of the VFF scheme.

III. Results and Discussion

In this section we present the global results of using the proposed telerobotic system in performing the above teleoperation tasks, the used CAT tools, and recommendations on how to improve the man-machine interfacing in the telerobotic system.

A. *Analysis of teleoperation tasks*

In this section we present the results of using the proposed telerobotic system in performing peg-in-hole insertion and assembly operation. These tasks are selected because they require effective interaction between the operator and the remote task involving fine motion, force feedback, and stereo vision. The results are limited to the period of interactions with the environment such as the insertion phase in peg-in-hole operation and 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 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.

Each of the insertion and part mating phases 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

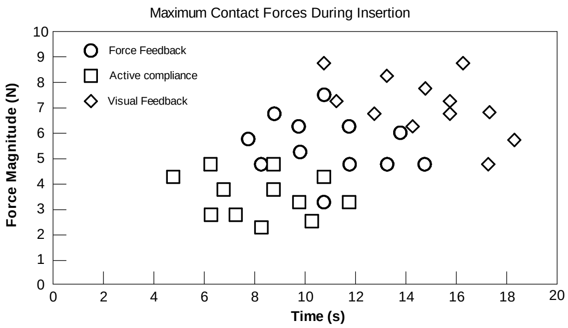


Fig. 5. Maximum insertion forces with respective task times

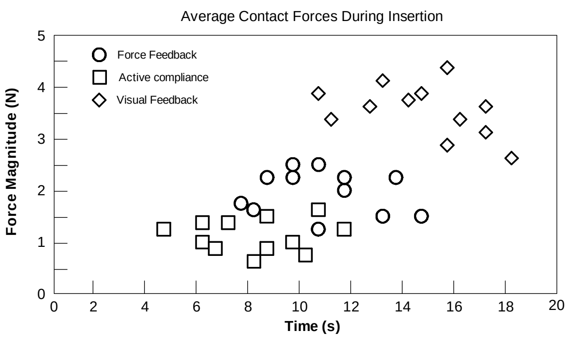


Fig. 6. Average insertion forces with respective task times

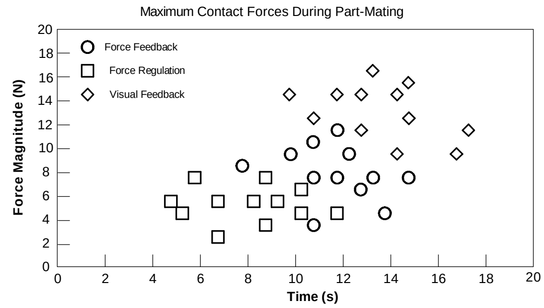


Fig. 7. Maximum assembly forces with respective task times

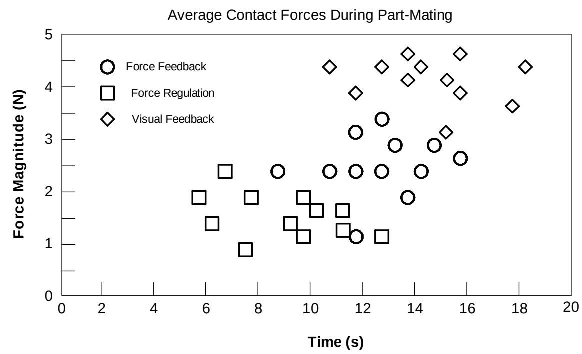


Fig. 8. Average assembly forces with respective task times

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. Combined results for all operators are presented. In total we have 72 plots for two phases. The F/M vectors are all computed at the origin of reference TF and sampled at 50 Hz on slave arm station. Both force and moment components are similar in terms of concluding remarks.

Figures 5 and 6 show the maximum and average force exerted during peg-in-hole insertion with respective operation times. The operators were satisfied with the quality of stereo vision provided during the experiments. Scheme V allows completion of the insertion but with the largest contact forces and completion times as compared to VFF and VAC. Occasionally V scheme may produce less contact forces and possibly less duration than the other two schemes. Stereo vision is one critical operator augmentation in telerobotics. However, the use of only visual feedback for any operator indicates that another critical feedback is missing as both peak and average forces dominate as compared to the other schemes. 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.

Figures 7 and 8 show the maximum and average force exerted during assembly of the pump with respective operation times. Similar to the insertion case, the VAC scheme outperforms the V and VFF but with less deviations both in maximum and average contact force. Table I shows the ratio of maximum and average force and task time of schemes V and VFF over scheme VAC for both insertion and assembly tasks. For the insertion, teleoperation with active compliance VAC allowed carrying out the tasks with the least task times and contact force. For the insertion, scheme V allows completion of the insertion but with significant increase in contact forces and 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. This shows the efficiency of supervisory approach and its local active 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 the assembly tasks, teleoperation with VAC is still ranked first but with less advantages as compared to the case of the insertion. The reason is probably due to operator ability to combine force feedback with 3D perception in the critical phases of the part mating.

In both insertion and assembly, VAC contributed in reducing peak and average contact forces as compared to both V and VFF schemes especially in the case of the insertion. VAC equally reduced task time for each of the FF and V schemes in both of insertion and assembly tasks.

Comparison of force and task time in insertion and assembly

	Force Magnitude		Task Time
Operation(ratio)	Maximum	Average	duration
Insertion (V/VAC)	1.93	3.85	1.76
Insertion (VFF/VAC)	1.45	1.89	1.33
Assembly (V/VAC)	2.33	2.74	1.55
Assembly (FF/VAC)	1.27	1.63	1.36

TABLE I

PEAK FORCE AND TASK DURATION FOR V AND VFF VS. VAC

IV. Comparison to others

In virtual reality based teleoperation [1], [2], [3], [8] the operator plans an operation using a model, the plan controls a slave arm, and slave arm transmits back parametric feedback. The primary issue is operation safety. Mainly off-line approaches are used and teleoperation is carried out on a static environment with no dynamic interaction reported. However, in [4] graphic animation of robot kinematics, dynamics, friction, and impact forces used in a closed loop control provides the operator the feeling of repulsive forces which allowed to carry out peg-in-hole insertion. In this paper direct teleoperation, CAT tools, and supervisory control are used to improve teleoperation effectiveness.

We concur with [9] on the importance of kinesthetic force feedback in assembly operations. We extended direct teleoperation by using compliance control. In comparison to [5] our proposed VFF and VAC schemes have similar effects in modifying task trajectory. The active compliance controller continuously searches corrections in tool position and orientation that reduce tool external F/M. Proposed VAC reduced peak contact forces and task time as compared to kinesthetic force feedback with vision in insertion and assembly tasks. The wrench mapping of [10] is comparable to proposed tool motion and force mapping. However, our dynamic mapping scheme showed to be useful tool for many tasks where the point of interest is function of task state.

V. Conclusion

Insertion and assembly of a water pump were evaluated using (1) stereo vision V, (2) vision and force feedback VFF, and (3) vision and active compliance VAC. Active compliance is has been used as assistance to direct teleoperation in addition to indexing and scalability 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. Scheme V allowed to complete the above tasks but resulted in the largest contact forces and task times as compared to VFF and VAC. In contact centric tasks, like insertion, VAC noticeably outperforms V and VFF and provides task quality control. In multi-objective tasks, like assembly, VAC and VFF are closer in peak and average force as well as in task times. However, VFF has variable delivery as it depends more on operator skills. Button-controlled indexing and scalability proved to be the most frequently used tools. Force feedback and active compliance are critical tools for extending human eye-hand motion coordination and dexterity to remote work in hazardous, hostile, and un-accessible environments.

VI. Acknowledgement

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