Force-Based Compliant Behaviors to Augment Telerobotics

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***Abstract*— Analysis of direct teleoperation with force feedback indicates that humans have difficulties perceiving the direction and amount of reflected force. Locally implemented force-based reactive behaviors provide accurate and timely feedback to assist in replicating human skills and dexterity. The contact forces between the slave arm tool and the environment is analyzed using three settings. First, the user-controlled teleoperation with networked force feedback. Analysis of contact with the environment indicates that the use of high force gain improves operator sensitivity but may cause instability in pre-contact and post-contact phases. Second, programmed compliance at slave arm is used to selectively convert sensed forces into corrective motion to minimize contact forces. Third, a supervisory mechanism based on a user-controlled active compliance behavior is proposed for teleoperation. A user-controlled compliance loop at the slave arm improved contact stability and provided an effective supervisory control. Light and stiff arms are highly recommended to reduce the degradation in telerobotic synchronization caused by elasticity in linkage transmission and by the network delays. Force based compliance behaviors provide controllable compliance both in amount and direction and (2) shorten feedback delays.**

***Index Terms*— Distributed application framework, reflected force feedback, man-machine interface, Telerobotics.**

I. INTRODUCTION

Force-based reactive behaviors are essential in telerobotics to assist in replicating human skills and dexterity at the remote work place. Analysis of the force feedback during the micro surgeries [1] 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 be able to sense them. Thus, the surgeon may operate with little or no tactile feedback which increases the potential of tissue damage.

The contact forces [1] measured at the tip of a microsurgical instrument are used to control the motion at the micrometer resolution for force-feedback of no less than 5 mN. The use of force-feedback in remote endoscopic surgery [2] proved to be beneficial. The slave manipulator accurately and quickly mimic the movement of the master arm at low speed; and the master arm satisfactorily reproduced the force.

Analysis of force feedback in micro-level tasks [3] allowed the design of a micro-gripper in which strain-gauge force sensors are interfaced to a haptic arm to let the operator feel the grasping forces and pulses in the micro vessels. This system has been employed successfully to differentiate tiny samples (100 pico-meter width) of human skin which were freshly excised from the areas around the fingernails of three volunteers.

Force-feedback is also employed in the Adaptive Impedance Control (AIC) at the slave arm as a shared-control strategy for teleoperation. Adaptive impedance control [4] provides a robot with the ability to interact flexibly in the uncertain (or unknown) environments. For instance, AIC may correct the slight horizontal misalignments which arise due to the uncertainties. Using a pre-planed insertion path, AIC reduces the jamming forces by finding the desired position adaptively to follow the optimal path from the current position; the optimal path is continuously updated based on environmental constraints.

A task-oriented micro/nano space teleoperation system [5] uses a mixture of direct and task oriented modes that are activated using a set of visualization and manipulation tools with some force monitoring. The high-level motion commands are used to avoid collisions. The approach is faster and safer with higher accuracy than the direct teleoperation given the presence of dominant electrostatic forces and the possibility of tool jams.

A six-axis force reflective hand controller (FRHC) [6] is evaluated using kinesthetic and stereo video. The operator position is mapped to slave arm both in position and velocity. Evaluation of a drill task indicates equal task times but with noticeably lower cumulative variance and peak forces where either visual or kinesthetic force is used with stereo vision. Force feedback is particularly useful in the case of unobstructed camera view leading to a low fidelity views.

In the deep space teleoperations, the usefulness of force feedback is limited because of the time delay in getting the feedback after performing the actions. To overcome the unexpected problems which may arise due to the time delays, a sensor-based motion-planning [7] is proposed. A bilateral control between a master arm and a graphical 3D slave arm. Sequence of fine motions can be performed on a graphical slave arm which in turn provides the operator the feeling of repulsive forces. The selected sequence is transmitted to the remote slave arm which is supervised by a sensor-based motion-planning algorithm under impedance control. Peg-in-hole assembly is successfully accomplished using this method [8].

In this paper, we study how force feedback can be used to program reactive behaviors to augment a networked telerobotic system. The contact forces between a slave arm tool and the environment is studied using (1) direct teleoperation with force feedback displayed on the operator, (2) force-based reactive compliance behavior at the slave arm, (3) active compliance as supervisory mechanism in networked teleoperation.

The paper consists of six sections. Section 2 presents the proposed telerobotic system. The evaluation of tele-operation with force feedback and complaint behavior are presented in section 3. The implication on the design of telerobotic systems is presented in Section 4. We conclude in Section 6.

II. Telerobotic System

The most common telerobotic system is based on a master arm station (MAS) and slave arm server station (SAS) which are interconnected by a computer network integrating bilateral motion, motion coordination systems, teleoperation tools, stereo vision, and force feedback. Motion scalability establishes a mapping from human scale to an arbitrary target teleoperation scale (micro, nano, etc). The System performance is measured by: (i) the extent to which telerobotics preserves human manipulative dexterity and (ii) the fidelity in translating the physical laws from one scale to another.

The MACS and SASS are implemented in client-server architecture that reliably transfers stereo, force, and command data. Moreover, MACS and SASS use the distributed software approach so that modification of a module in one station does not require any changes in the other station (i.e. the module functions are distributed in different software components). Specifically each module communicates with its counterpart using a standard inter-process communication system (MSF .NET remoting).

A. Position and force mapping at slave arm

The SAS consists of a 6-dof PUMA slave arm and a **6-dof** wrist force sensor [9]. The kinematics of slave arm is represented by means of three frames: (1) a fixed world frame (R_w) at arm origin, (2) an effector frame (R_e), and (3) a user defined tool frame (R_t). The controllable frame R_e is represented by its 3×1 position vector ($E_w(\theta)$) and its (3×3) orientation matrix ($M^e_w(\theta)$), where θ is the slave arm joint vector and w refers to R_w. The tool frame R_t is user or system defined by its position vector T_t and orientation matrix M^t_e of tool frame R_t with respect to frame R_e. The position of the tool point is defined by $T_w = E_w + M^e_w(\theta)M^t_eT_t$.

The slave station receives a command from the master arm station to translate the tool frame R_t by ΔT_w and to rotate it by ΔM_t. The operator motion can be efficiently mapped onto the tool frame when the translation is specified in tool frame, i.e. ΔT_t. The new arm controllable position vector is: (1) $\Delta E_w = M^t_w(I-\Delta M_t)T_t + \Delta T_w$ if the operator hand is mapped to slave tool (relative), or (2) $\Delta E_w = M^t_w(I-\Delta M_t)T_t + M^t_w\Delta T_t$ if the operator hand is mapped to slave world frame (absolute), where $M^t_w = M^e_wM^t_e$. The new effector orientation matrix (controllable) becomes $\Delta M_e = M^t_e\Delta M_tM^e_t$.

The PUMA reads current joint vector θ and computes effector position $E_w(\theta)$ and orientation $M^e_w(\theta)$. The target effector position and orientation are $E^+_w = E_w(\theta) + \Delta E_w$ and $M^{e+}_w = M^e_w(\theta)\Delta M_e$. The inverse kinematic model $\theta^+ = G^{-1}(E^+_w, M^{e+}_w)$ provides the joint vector θ^+ that moves the tool by the commanded translation ΔT and rotation ΔM. θ^+ is sent to slave arm motion controller. Incremental change in operator hand frame R_{op} is superimposed on tool frame R_t. For example, when R_{op} is tilted the remote tool frame R_t is tilted by the same angle.

B. Mapping force feedback

The used force sensor consists of two parallel plates p_1 (frame R_e) and p_2 (frame R_s) interconnected by three elastic links. The motion of p_2 with respect to p_1 is measured by a (1) translation vector ΔS_e, and (2) orientation matrix ΔM_e. The sensor structure allows finding ΔS_e and ΔM_e as functions of the six sensing signals. The sensor frame R_s is located between R_e and R_t. An external force applied to the tool causes a translation vector $\Delta T_e = \Delta S_e + (\Delta M_e - I)M^t_sT_t$ to the tool frame origin and a change $\Delta M_t = M^s_t\Delta MM^t_s$ in R_t orientation. Since $M^t_e = \Delta MM^t_s$, the tool deflection vector is $\Delta T_t = M^s_t\Delta M^{-1}\Delta T_e$.

C. Active compliance

Active Compliance (AC) is a control loop that is activated by the remote operator. It consists of continuously sensing the force exerted on the tool, evaluating a proportional force error based on a desired force, and converting the error into a position increment to reduce the force error.

AC is a control loop that repeatedly converts the measured force into an incremental motion for the slave tool. The force (F_t) and moment (C_t) vectors are computed using vectors ΔT_t and $M^s_t\Delta MM^t_s$. Using the passive compliance matrices for linear (K_l) and rotational (K_r) motion of the tool we compute the force $F_t = (f_x, f_y, f_z)^t = K_l\Delta T_t$ and moment $C_t = (c_x, c_y, c_z)^t = K_r\Delta M_t$ vectors. F_t and C_t are used to: (1) display the reflected force feedback at the client station, and (2) implement active compliance mechanism as a supervisor control strategy.

To increase teleoperation flexibility the user may select setting up active compliance over a sub-set of tool axes while other axes are kept under position control. In this case the selected components of computed force F_t and moment C_t vectors are fedback as elementary tool translation ($\Delta T = AF_t$) and rotation ($\Delta M = BC_t$); where A and B are two 3×3 diagonal matrices that determine the selected axes.

D. Master arm station (MAS)

MAS has a graphical interface to set up its connection to SAS and to monitor its operations. To increase flexibility, a set of button-controlled teleoperation functions are added near the operator's finger tip. The operator can use them conveniently to control the MAS. The teleoperation functions attached to these buttons are: (1) real-time rendering of the operator motion, (2) indexing, and (3) space scalability. Each of these functions are described in the following paragraphs.

Real-time rendering of the operator motion (master) and display of force feedback is implemented as follows. Rendering needs two major inputs: (1) the joint vector read from position sensors and (2) force data coming from the remote side. Arm kinematics model $G_M(\theta)$ allows computing the current operator hand position vector X^+ and orientation matrix M^+, where θ is the arm joint vector. Using last references X and M, it computes the variations $\Delta X = X^+ - X$ and $\Delta M = M^t M^+$ with respect to reference. MAS sends the above computed variations to SASS as an incremental motion command for the slave tool frame. In addition, MAS transforms the received force feedback into motor torques and applies them to the appropriate motors connected on the master arm to display the force feedback on operator hand.

The indexing function allows the operator to change the current reference position of the master arm to a desired convenient position. When the indexing function is pressed, the system disables the transmission of operator movements to the slave arm, and sets the master arm's reference to the position chosen by the operator.

The scalability function is useful in performing fine movements. When this button is pressed, the increments in master position vector (ΔX) and orientation matrix (ΔM) are scaled-down by a scaling factor (s) before transmitted to the slave arm. The calculation of the scaled position and orientation vector is as follows.

The variation in the operator hand orientation matrix (ΔM) can be seen as a sequence of three euler angles, i.e. $\Delta M = R_x(\alpha_x)\ R_y(\alpha_y) R_z(\alpha_z) = R_{xyz}(M)$, where R_u is a rotation matrix about axis u and R_{xyz} is the product of three rotation matrices sets for ΔM. Since ΔM is known, solving equation $\Delta M = R_{xyz}(M)$ allows finding the three angles which is denoted by $(\alpha_x, \alpha_y, \alpha_z) = R^{-1}_{xyz}(\Delta M)$. Using an operator-controlled scale factor s, the scale function becomes $(\Delta X, \Delta M) = ((X^+ - X) * s, R_{xyz}((R^{-1}_{xyz}(\Delta M)) * s)))$. To avoid singularities at $\pm\pi/2$, the three Euler angles are computed for the variation in the operator orientation matrix ΔM.

III. Evaluation

A. System configuration

The client and server are run on PCs having 2-GHz Intel P4 processor with 1GB DRAM and 512 KB cache. An anthropomorphic, 6 dof, master arm is used with steel-wire transmission system. The slave arm is a PUMA 560 robot arm. Each of client and server PCs is attached to a campus network by using a 100 Mbps NIC card. The server PC is interfaced to two Sony Handycam digital cameras using a 400 mbps FireWire PCI card. Both client and server PCs run under MS Window 2000. The server software uses MS Visual C++ with .NET framework 1.1. The server is implemented using MS Visual C#.

B. Brief telerobotic features

Analysis of telerobotic delays through three campus routes was carried out while streaming of video, force, and commands. A sampling rate of 120 Hz is achieved for force feedback and 50 Hz for operator commands. Stereo video transfer operates at a rate of 17 fps. Total reference delays for force and stereo are 8 ms and 83 ms, respectively. Overall round-trip delay is 183 ms (5.5 Hz) when slave arm is operated at 10 Hz.

The effectiveness of the framework and concurrent execution of its various computing and communicating threads has been assessed in the experimentation of the following tasks: (1) peg-in-hole insertion, (2) assembly of a small water pump, (3) operating drawers, (4) pouring of water, and (5) wire-wrapping. The above experiments involve the completeness, modularity and flexibility of proposed telerobotic framework when rich and heterogeneous sensory data (video, force, and command) was exchanged between client and server. A summary of results [10] is as follows: (1) teleoperation tools are very effective and need to be developed, (2) advanced motion coordination reduces teleoperation time and operator mental effort, (3) active compliance at server station is more effective than operator reaction using force feedback.

C. Teleoperation with force feedback

In direct teleoperation the operator uses a master arm to (1) prescribe his hand motion to slave arm, and (2) display coordinated force feedback on the master arm motors to reproduce the tool force at the operator hand. Ideally contact teleoperation uses reflected force feedback to allow the user operate on the environment while minimizing contact forces, a property that the human arm has high-fidelity through the use of natural visual, haptic, and force information. The operator has no training for the experiments and the recorded data is made from the early experimentation. The objective of this experiment is to study the teleoperation contact made between the slave arm tool and the environment. There are three contact phases: (1) pre-contact as the transfer from free-space to contact, (2) contact, and (3) pre-release as the transfer from contact to free-space. In addition the operator is provided with a force display to watch the currently displayed three components of force and moment. Following the contact phase the operator was asked to exert and maintain a force of 1 N on the target for no less than 3 seconds prior to release contact. Internet teleoperation involves a large control loop extending from the slave arm station to remote user is established including the user reaction time, the mechanical latencies, the network communication delays, and processing overhead. The sampling frequency of the local compliance loop is about 5 Hz due to the mechanical delays of the PUMA slave arm. A force feedback gain FFG is used to adjust the displayed force value to a proper sensitivity level for the operator. The master arm can display up to ± 15 N force in any direction which represent the saturation level for any displayed force in excess of the above limits.

Figure 1 shows the interaction during contact between the tool and (1) a rubber (Plots a and b), (2) a human muscle tissue

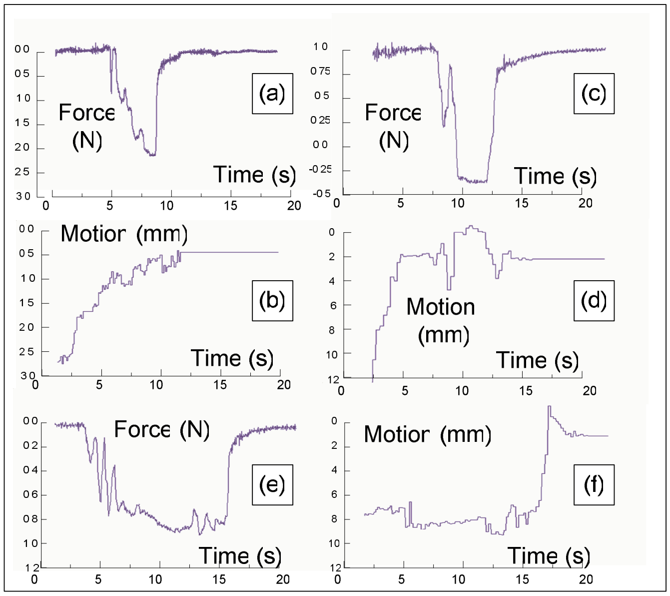

Fig. 1. Bilateral teleoperation with reflected force feedback

(plots c and d), and (3) rigid body (plot e and f). For each of the above three cases the plot shows the force measured at the slave arm tool (plots a, c, and e) and motion reaction (plots b, d, and f) made by the operator at master arm to zero the displayed force feedback.

In general, both the pre-contact and pre-release phases are subject to instability represented by the vibrations shown in the above figures. For low values of FFG (below 5) the operator does not properly feel the contact and teleoperate in quasi open loop fashion. For moderate values of FFG (from 10 to 20) the force feeling is appropriate but with the instability shown in the pre-contact (also in pre-release). For higher values of FFG the teleoperation becomes dominated by instability which is driving the operator. The operator needs to adjust the displayed force gain to a proper sensitivity level in connection with overall system stability. In the contact phase the operator feels the wall effect as the master arm produces a repulsive force constraining the operator motion in the direction that increases the above constraints. The force displayed on the master arm allows the operator to feel the mechanical impedance of the environment such as the elasticity feature of some objects like the spring or rubber for which the interaction force feedback was transmitted and reproduced into similar physical constraints on the operator hand.

The instability and its vibration frequency depend on: (1) the stiffness of the target, (2) value of FFG, and (3) total system round-trip delay (RTD) of 183 ms. Note that the RTD does not include the decision making time by operator. Therefore the sensing-to-reaction rate or operator-tool interaction cannot exceed 5.5 Hz if we exclude the human factors which vary from one operator to another. Stiff targets produce prompt bouncing contact forces and therefore produce higher vibration frequency (Figure (e-f)). The vibrations for rigid objects are greater and faster than those of the rubber or the tissue. Contact forces transmitted from the scene return a bouncing force from the operator. This process continues until the contact is firmly engaged which amortizes the above vibrations. A high feedback gain and a fast contact may drive the telerobot out of control, i.e. the master arm becomes instable which makes teleoperation quite poor. Stable contact for the rigid and spring objects requires the use of moderate gains (less than 20) as compared to the case of the tissue. However, higher gain values provide finer sensing and earlier detection of contact but with the potential of unstable teleoperation.

D. Active compliance at the slave station

Implementing active compliance (AC) at the slave arm consists of activating a local loop, at the slave arm station, in which the measured tool force at a selected compliance center is converted into a corrective position or velocity. The result is a slave arm that acts as a 6 dof compliant mechanism that continuously adjusts the tool position and orientation, at the compliance center (CC), to minimize the forces and torques exerted at CC. For this the sensed force at the wrist is used to evaluate the force exerted at a selected CC tool position. Similarly, measured forces (torques) at CC are converted into corrective translations (orientation). Thus CC can be set by the remote user anywhere in the vicinity of the slave arm tool depending on the task.

AC loop needs not be activated on all the three force and three torque components. AC can be used to control any subset of the six possible tool dofs so that the remaining dofs are left under position or velocity control. Thus, AC can be activated on selective dofs while the other dofs are left under position control, i.e. generated by (1) a local program, or (2) operator motion through teleoperation. The compliance loop and the CC location can be activated and controlled by the remote operator at the master arm station.

AC presents a supervisory mechanism to support networked teleoperaton by creating a remote loop running at the slave station which substitutes for some of the operator interaction. This reduces the frequency of interaction between operator and remote workspace which saves network bandwidth and eliminates the potential of instability that might be caused by transmission delays and jitter.

For teleoperation, AC is useful to provide the operator a force compliant slave arm that is lead by the operator into tasks (like insertion or assembly) that create force constraints which are locally canceled by the AC loop without direct intervention from the operator. Canceling the external force constraints on the tool means that AC corrects the tool position and orientation to reduce jamming forces during insertion or assembly or to reduce forces that occur during tasks involving contact with the environment.

The AC at the slave arm station is studied here through a set of experiments. Each experiment consists of 1) selective activation of AC loop for some dofs while the other dofs are left under a trajectory control program, (2) exposing the slave arm tool to contact with the environment to create external force constraints, and (3) plot the reactive motion and discuss its performance. The experiments are the following:

1) The tool frame is moved at constant speed in one horizontal direction while the vertical direction is under

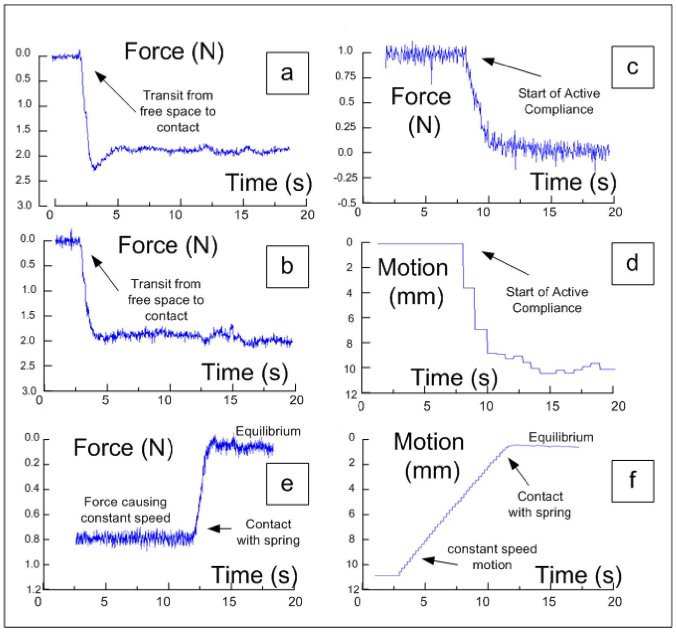

Fig. 2. Active compliance functions at the server station

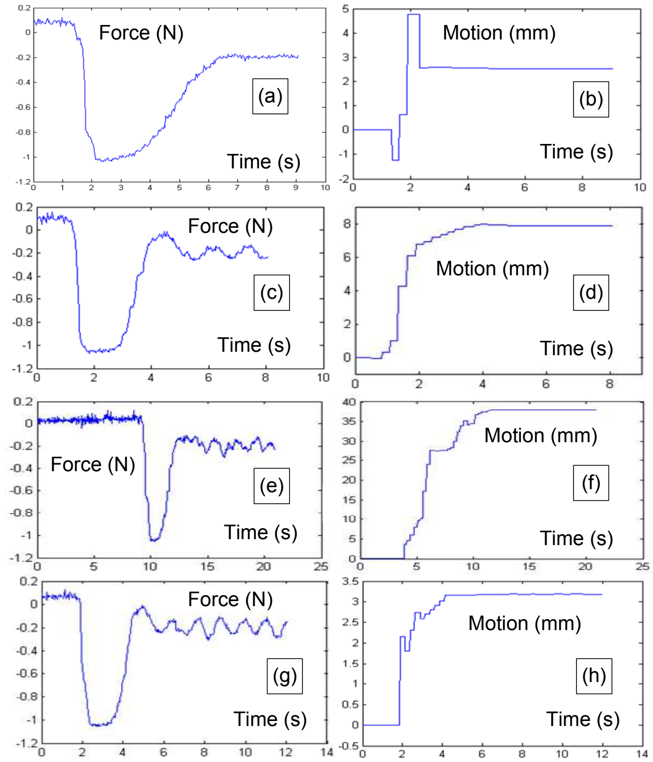

Fig. 3. Shared-control using active compliance and bilateral teleoperation with reflected force feedback

force control with a desired force of 2N. A peg ended with rolling wheel is attached to the tool. The wheel hit an inclined plane (20^o) and the force regulation lead the tool to climb the plan. A downward force component F_d is desired to maintain contact and the motion correction is defined as $\Delta T = A(F_d - F_t)$. F_d is applied following the first contact. F_d is selected and set through the client user interface. Figure 2-(a) shows the measured force during the motion where the dynamic force is very close to the desired value but with some overshoot. Figure 2-(b) shows the measured force when the motion correction contains a dumping term defined as $\Delta T = A_p(F_d - F_t) - A_v F_t^{'}$, where $F_t^{'}$ is the variation in measured force and A_p and A_v are two gain matrices.

2) The tool is manually moved to press a spring and instantly released. Figures 2-(c) shows the force measured as caused by the spring reaction and the position corrections (part d) made by the active compliance controller according to $\Delta T = A(F_{spring} - F_t)$, where F_{spring} is the spring force exerted on the tool. The corrections made by the active compliance controller iteratively reduce the resulting force (compliance) on the tool. At equilibrium the tool converges to a position where the external force is null.

3) A weight of 0.8N is set on the tool causing a vertical motion of the tool. A spring is placed in the motion direction. When the tool (with weight) hits the spring the measured force is nearly zero due to balancing between the gravity induced by the weight and the spring reaction to the above force as illustrated in Figures 2-(e) and (f) show the transient force and the position convergence, respectively

E. Teleoperation using AC

Figure 3 shows the force feedback generated during teleoperation while the force feedback was displayed on the operator and an active compliance control was activated at the slave robot. Figures 3-(a), (c), (e), and (g) show the force measured at the tool during contact with a spring, rubber, tissue, and a rigid object, respectively. The corrective motion carried out by the active compliance in each of the above cases are shown on Figures 3-(b), (d), (f), and (h), respectively. The position corrections ΔT made by the active compliance controller are proportional to force error defined as $\Delta T = A_p(F_d - F_t)$, where A_p is a gain matrix. The corrections made by the active compliance controller are effective to reduce the contact forces. These corrections cause the contact force to return to the null zero level at different speed depending on the contacted object. Slow and smooth return to zero is found in the case of the spring. However, in all of the other three observed cases some oscillations are taking place at equilibrium, i.e. at convergence of corrections or pre-release phase. The largest oscillations are observed in the case of the rigid object.

IV. IMPLICATION ON THE DESIGN OF TELEROBOTIC SYSTEMS

In direct telerobotics the reflected force feedback is best displayed at the operator hand center to let the operator feels the directional force and torque that are measured at the tool tip. In real implementations, there are many imperfections in the reproduction of the force feedback like the accuracy of the sensor and its model, the master arm link inertia and gravity effects, and the elasticity introduced by the wire-based linkage. The above effects make it difficult to the operator to accurately determine the direction of the displayed forces/torques, a critical capability to enable accurate motion correction. The used master arm is designed to reduce these effects because its last 3-revolute dofs have three concurrent rotation axes that intersect at the operator hand center which makes the operator feels equal mechanical impedance in all the three hand rotations. Although the link weights were significantly reduced so that the master arm overall weight is 3 Kgs the arm can display force within a maximum of 15 N.

The anthropomorphic arm structure is adequate as a man-machine interface but the elasticity of its long wire-based transmission create uncontrollable intermediate states (ISs) in the task-operator transmission chain such as the motor shafts and reduction wheels. The following series of events takes place before transmission of operator reaction. IS receives the displayed force feedback from slave station and reacts before the operator due to the elastic transmission. IS reaction is sampled by the master arm controller, transmitted through the network, and reported by the server on the slave arm motion. During the above back-pressure time, the reaction is transmitted from the master arm motor shafts, through the linkage, to the operator which takes some time (up to 200 ms) to make a decision, react, transmit reaction through linkage, master arm samples reaction, and transmit it to slave station.

On the other hand, the master arm work space is relatively large ($600mm \times 600mm \times 600mm$). Teleoperation tasks involving assembly tasks indicate that the operator frequently uses the space indexing to re-map the operator dexterity area (master arm) to current slave arm configuration. In other words, the effective master arm work space is no more than 20% of the above master arm work space. A smaller master arm with tight wire-based transmission is expected to reduce the transmission elasticity, and consequently the oscillations during the pre-contact and pre-release phases.

Analysis of direct teleoperation with force feedback allowed identifying four major problems. First, a human receiving force display has difficulties perceiving the direction and magnitude of the displayed force. Second, stable contact control requires complex management of many parameters like the force feedback gain. Third, anthropomorphic master arms have uncontrollable intermediate states which complicate toleoperation. Fourth, the transmission delays lead to stop-and-wait teleoperation. Locally implemented force-based reactive behaviors, like active compliance, provide accurate and timely feedback to assist in replicating human skills and dexterity. To shorten the loop a reactive force control can be activated at the slave site to provide some active compliance during direct teleoperation. In other words, coarse slave motion is controlled by the remote operator while highly interactive local force control produces the needed tool compliance that minimizes contact force. In summary, the user leads the slave arm to contact the environment while the local controller corrects the tool positioning to minimize contact forces. The success of AC reactive behavior is due to its locality which avoids communication delays and its adaptation to sensed forces which avoid a non-linear and late operator reaction.

V. Conclusion

Direct teleoperation with force feedback exhibits some instability due to linkage elasticities in pre- and post-contact phases. In addition accurate perception of directional force feedback is difficult to a human operator. A qualitative contact characterization is presented based on force feedback gain and environment impedance. To reduce environment variation an active compliance mechanism is proposed as a local reactive behavior (loop) at the slave arm to minimize contact forces. It acts by converting sensed forces into corrective motion to zero external forces. Active compliance is successfully used as supervisory mechanism in networked teleoperation with force feedback. The operator drives the slave arm, which is under active compliance control, and engages it in contact with the environment. The selective and operational features of the reactive controller can be set up by the operator during teleoperation. This scheme resembles a two-level subsumptive control.

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