Force-Torque Interpretation In Intermediary Telepresence For Remote Manipulation

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***Abstract*— The paper presents force-torque interpretations in intermediary telepresence for remote manipulation. Methods of reconstruction of force-torque data and algorithms to depict contact forces are presented in this paper. Real time force trajectory, the accuracy of the force trajectory and the state of the remote site in terms of wrench state are also described. In addition, options to take corrective steps in case of remote manipulator malfunction or unforeseen forces acting on the environment are discussed. Experiments are conducted to demonstrate the contact perception of remote manipulation tasks.**

Keywords*— *force-torque interpretation, force trajectory, contact perception, force

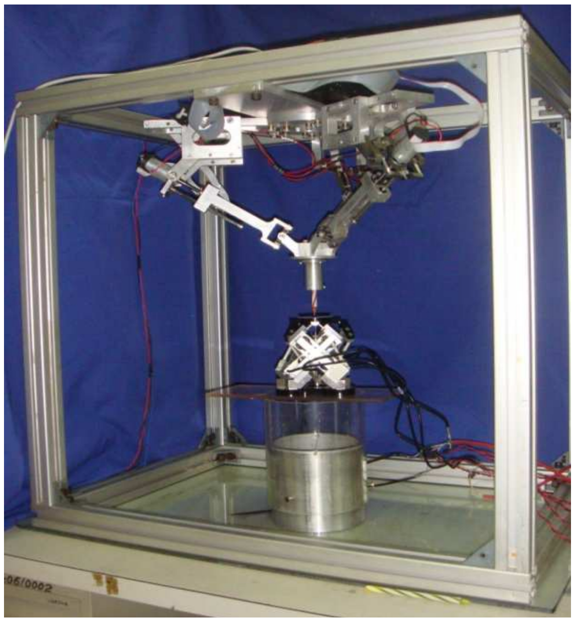
I. INTRODUCTION

Making a remote manipulation experience same as the direct manipulation experience is a challenge many researchers have taken up. The feasibility of long distance remote manipulation emerged because of the aspects of telemanipulation and telepresence. The practical definitions of telemanipulation and telepresence are originally given by Sheridan [1]. There has been extensive research and development taking place to give a real feel and look for the remote manipulation [2, 3, 4]. A full-fledged telepresence system is very complex, often not feasible and also not warranted for many tasks. The requirement is often such that the manipulation has to be conducted remotely with an operator in the control loop. The operator in the loop should play a master or supervisory role and be able to manipulate and also take safety or corrective action. Posture control, its interpretations in terms of end effector position and orientation are well studied and interpreted. High precision posture trajectory and supervision in remote manipulation is achieved [5, 6]. Interpreting wrench always posed challenges because wrench is a 6 dimensional free vector comprising of three pure force components and three torque components. In-contact remote operations are to be conducted in wrench control in order to achieve superior and safe remote manipulation. The reflected wrench is constituent of many components arising from damping and friction [5]. The task lies in identifying required constituent and filtering unwanted constituents for correct estimate of the wrench at the remote site. The point of application of force is very crucial information in contact based analysis and the force as a free vector definition does not encapsulate this information. Force-Torque interpretations by human feel, suffer greatly from subjective distinction while the computer based master interface lacks in clarity of representation.

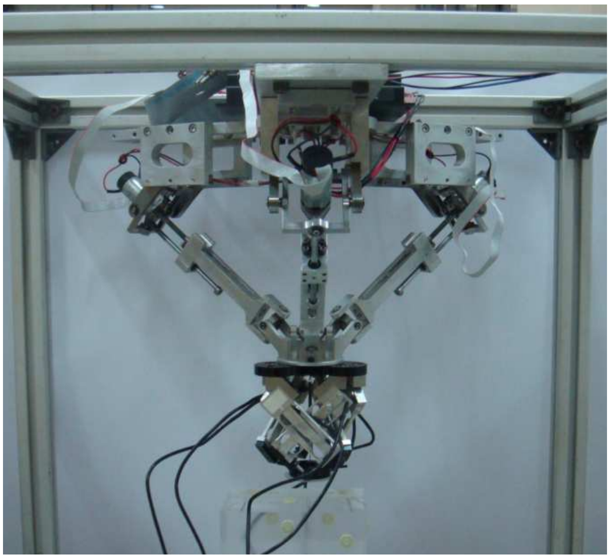
Tactile information during surface contact between remote manipulator and its environment is an important factor to recognize surface geometry, texture analysis, friction, etc. The review articles [7, 8] present the state of the art tactile sensing till the year 2013 explaining a variety of tactile sensors. Force-torque sensor and multi component force feedback are the critical components to develop a contact perception of the remote site. There has been lot of research work on multi-component force sensing devices. Dwarakanath et al [9, 10] discussed the design and development of such devices. The F-T device is generally placed in the wrist of the manipulator to avoid sensing of forces caused by friction, damping and inertial forces of the manipulator in force control applications.

This paper presents Force-Torque interpretations in practical intermediary telepresence to conduct the remote manipulation efficiently. This research is not based on the designer perspective rather it is solely on the user perspective. The solutions to the efficient remote manipulation are constantly evolving from a long time, the validity of solutions come directly from the comfort of the human in the control loop. In this research, the remote contact perception is displayed as the real time visual graphics display. A Graphics Master Interface (GMI) is developed to give comprehensive feel for the contact at the interface. Force feedback is an important component of the telepresence. Force diagrams re-constructed using multiple components of reflected force information are shown to be highly effective for an operator in gauging the force at the interface of the remote manipulator and the environment. The performance is measured by analyzing the ability to perform very fine force trajectory control and ability to assess the interaction of the remote manipulator with the environment. We present experiments conducted in the author's laboratory to study force feedback and presentation of feedback information at the master site. Both qualitative and quantitative assessments of the contact forces along the trajectory are ascertained.

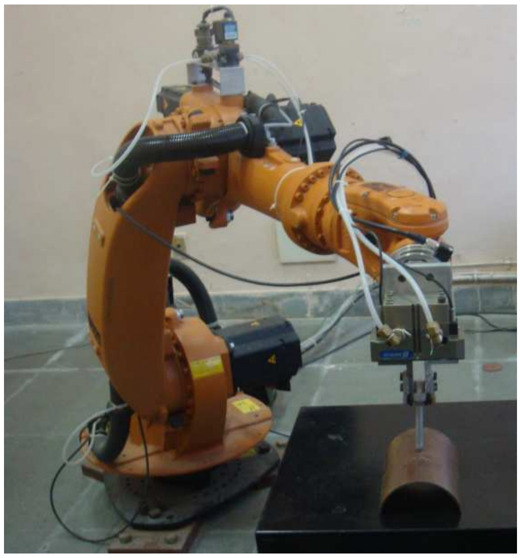
(a) Planar parallel Manipulator making an in-contact procedure with the environment fitted with a wrench sensor



(b) Spatial parallel Manipulator carrying a probe making an in-contact procedure with the job fitted on a wrench sensor



(c) Spatial parallel Manipulator integrated with a wrench sensor making an in-contact procedure with the environment



(d) Spatial Serial Manipulator integrated with a wrench sensor making an in-contact procedure with the environment

Fig. 1: (Color online) Typical arrangements of the manipulators along with the wrench sensor to perceive the contact in remote manipulations

Methods of reconstruction of force-torque data and algorithms to depict contact forces, real time force trajectory, the accuracy of the force trajectory and the state of the remote site in terms of wrench state are discussed in detail in the paper. The focus of the paper is to conduct a reliable remote manipulation with good contact perception of the remote site.

II. REMOTE CONTACT PERCEPTION AND WRENCH SPACE

The typical arrangements of the manipulators along with the wrench sensor to perceive the contact in remote manipulations are shown in Fig. 1. The wrench sensor integrated in all the arrangements in fig. 1 would form a direct relationship with the environment bypassing friction, damping and inertia forces at the manipulator joints and also filter the kinematic errors. Particular choice of an arrangement largely depends upon the application. However, the preferred choice is observed to be such that the stationary unit among environment or manipulator carry the wrench sensor. Apart from the arrangements shown in Fig. 1, the end effector contact forces are also perceived by sensing actuated joint forces and using Jacobian mapping equation 1. τ is the 6×1 joint force (or torque) vector, W is the 6×1 Cartesian force-moment (wrench) vector and J is the 6×6 Jacobian matrix.

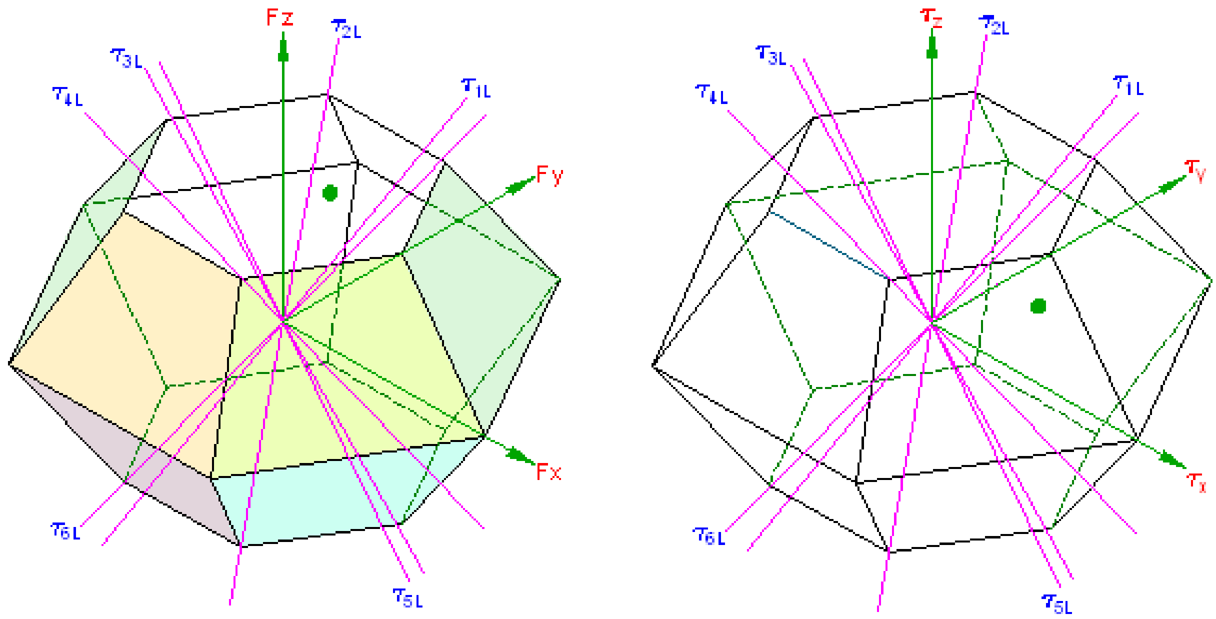
Experiments are carried out with various combinations of arrangements shown in Fig. 1 to develop wrench interpretation scheme for remote manipulation with intermediary telepresence. Robot wrench space in contact mechanics is analogues to robot work space in motion mechanics. The position and orientation space is important for the end effector motion; similarly, the force and torque space, at and about the point of contact, is important for force control operations. The capability of the manipulator to generate or to sustain a wrench at the points inside the workspace of the manipulator is termed as manipulator wrench space [11, 12]. The wrench space varies across the volume of the workspace. Wrench space is a combination of forces at a point and torques about the axes passing through the point.

$$\tau = J^T W \tag{1}$$

In all our remote manipulator operations, the co-ordinates of the point of contact are known from the task description and system model. The active guidelines to the user about the feasible region of the wrench space at the point of contact are of utmost importance. Polytopes are the exact representation of the joint capabilities in the task space. They also serve as the wrench estimate for a particular operation. To serve this as a useful feature, an active graphical wrench space window is activated during an in-contact operation. The user can perceive the state of the wrench and the wrench potential at the point of interest comprehensively. Fig. 2 shows the wrench space along with the wrench status of the manipulator. The magenta lines indicate independent joint axis of the manipulator and the length is proportional to the magnitude of the joint force/torque. The green spherical indicator ball always shows the current wrench status of the manipulator relative to the wrench space. The force/torque that it can further generate or sustain depends upon the status ball's position with respect to its boundary surfaces.

The wrench space analysis and representation not only gives the present status of the wrench field but also gives a clear insight on the available potential. Addition of this feature is advantageous in feedback analysis, unlike haptics, which merely gives the status feedback.

Fig. 3 shows the block diagram of the telemanipulation scheme explaining the flow of command, feedback and the components that are implemented towards telepresence in telemanipulation. The command flow and the feedback graphic display updates are constructed to take place within operational time period of the contact based operations. Several safety software modules are implemented to prevent accidents at the slave site due to common human mistake. For example, in case of abnormal changes in wrench field, the slave would come to a complete stop at its current position. Next section deals in detail with the depiction of the wrench field in an intermediary telepresence scheme.



(a) Force space

(b) Torque space

Fig. 2: (Color online) Wrench space at a point in the workspace

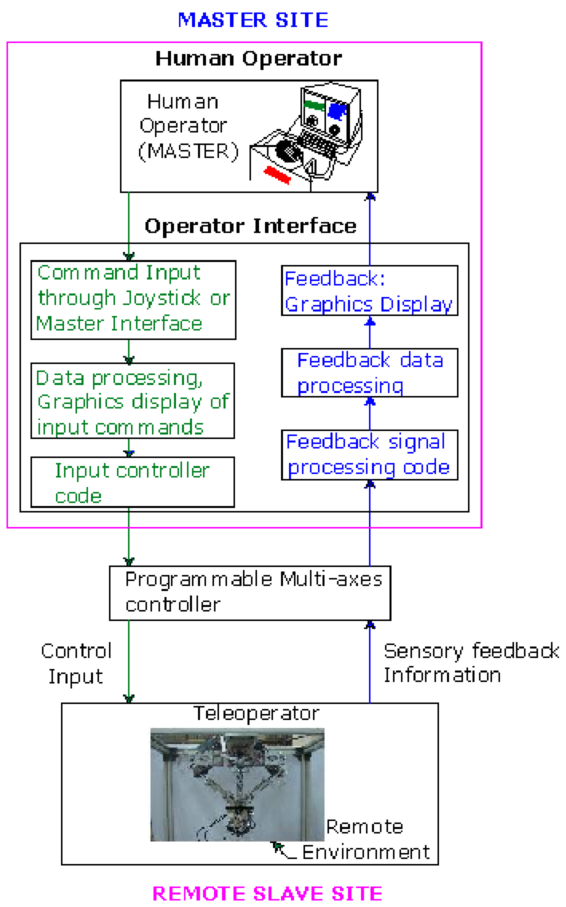


Fig. 3: (Color online) Design of flow of command in a telemanipulation set up

III. FORCE DIAGRAMS

This section deals with reliable and simple ways to display the wrench interaction of the remote manipulator with the environment. The context of the development is in-contact mode domain to conduct remote operations that take place inside the nuclear hot cell. The human access is very difficult but highly comprehensive status information is required. The concept can serve to automate several complex manipulations in the hot cell. It is observed that an operator is comfortable in studying the force diagram, which represents the intent of the operation. Force diagrams are constructed using wrench information. Objective assessments of contact forces along the trajectory were ascertained. Force diagrams are far more effective in assessing the contact force at the interface of the tool tip and the job than presenting six graphs comprising six components of the wrench vector. Experiments are presented to demonstrate this effect in detail.

A simple test to check the directional accuracy of the wrench display is conducted by applying forces to create moments in opposite directions. In all the experiments described here, the platform of the 6-axis force/torque sensor has served as a working surface. Suitable transformation matrix was used to get the origin of the sensor frame coinciding with origin of the XYZ frame. Fig. 4 shows the moment lines when the forces are applied so as to create opposite moments. The left side sketch of fig. 4 shows the six points (F_{z1},..F_{z6}), where the force is applied. The right side sketch of fig.4 shows the moment lines in response to the applied force. This test is repeated many times to observe the directional repeatability. It can be seen that all the response lines show an excellent directional accuracy, common intersection point and repeatability.

In another experiment, a computer generated circular motion sequence is given as an input for the remote manipulator. Fig. 5 shows the corresponding force diagram reconstructed from the force-torque data during contact. Fig. 5(a) shows the force diagram, when the tip of the remote robotic tool is in contact directly on a Perspex sheet kept on the workbench while drawing a trajectory. Fig. 5(b) shows the force diagram of same trajectory as in 5(a) but an additional sheet of paper is introduced between Perspex and the tool tip and Fig. 5(c) shows the force diagram, when two sheets of paper are introduced. The force diagrams capture the intent of motion sequence using purely force-torque information. Also the force feedback diagrams clearly demonstrate the gradual distortion in smoothness at the tool tip interface with the introduction of additional sheets. The clarity of this distortion at the interface was absent when we presented the individual components of the wrench vector.

A highly intricate contact mode operation is performed to evalulate the force diagram, a caricature of a popular personality is drawn on the surface. The moments produced by the drawing force are sensed and used to construct the force diagram in real time. The outcome after completion of the drawing is shown in the Fig. 6.

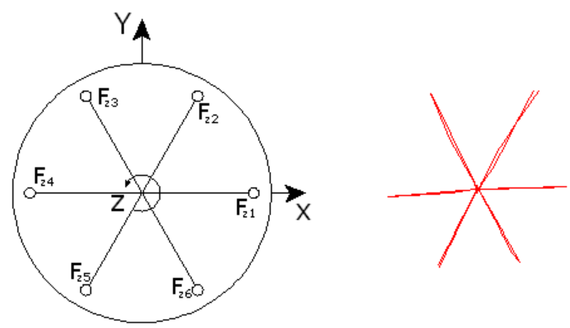
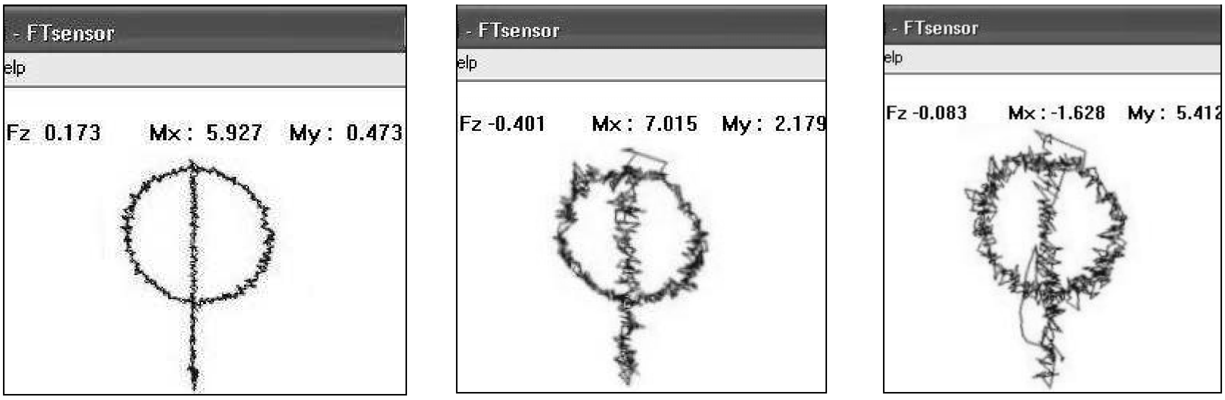


Fig. 4: (Color online) Application of forces to check directional accuracy and repeatability.



(a) Directly on Perspex sheet. (b) A sheet of paper on top of Perspex. (c) Two sheets of paper on top of a Perspex.

Fig. 5: Force diagrams of remote contact force trajectory

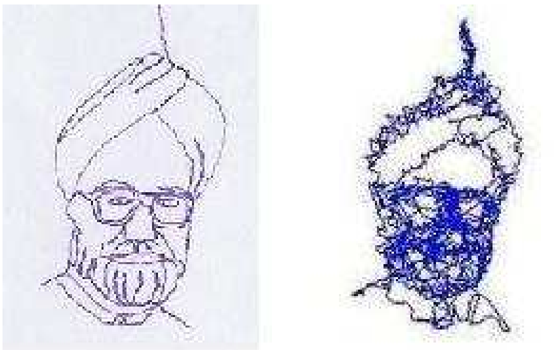
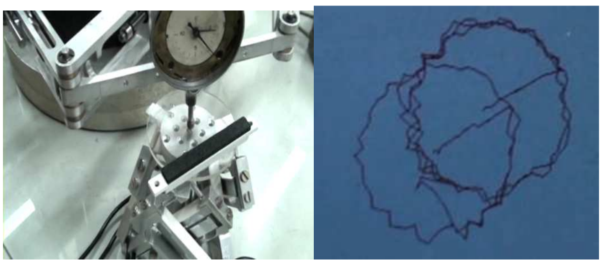


Fig. 6: (Color online) Intricate caricature drawn by the robot and the corresponding Moment-graph drawn using only sensed moment data



(a) Manipulator conducting a remote contact mode operation (b) Corresponding force diagram of the contact mode operation

Fig.7: (Color online) View of force disturbance at the remote site though force-diagram

A multi circular motion sequence is given as input to the remote manipulator as in the clip shown in the Fig. 7. After the completion of one rotation, a static force disturbance is introduced by placing an object on the surface of the work table. The master operator can assess the magnitude and direction of the force disturbance. The distance and the direction of the subsequent circular force diagram give a measure of the magnitude and direction respectively. The constant offset distance of the corresponding points of the circle indicate that there is static type of force disturbance. Above details will come into immediate comprehension of the operator because of the force diagram.

A. *Simulation results of 3-D force monitoring experiments*

Feasibility of generating 3-D force diagrams was found by simulating the 3-D scenario. A co-ordinate frame O(XYZ) is defined on the working surface of a wrench sensor. A solid transparent cylinder was placed upright on a working surface. The center of the base of the cylinder is made to coincide with (4, 4, 0) as shown in Fig. 8(a) and 8(b). A predetermined contact force is applied on the cylinder. The robot is assumed to traverse on the curved surface of the cylinder along a spiral path, applying contact force with regular increments in Z co-ordinate (see Fig. 9(a) and 9(b)). The scenario is shown in Fig. 1(d), but in simulation, the cylinder is assumed to be in upright condition. Forces and Moments in response to the applied force are calculated with respect to the sensor frame, O(XYZ). Force diagrams are constructed by plotting the moment about X, Y and Z axes of the sensor frame.

Fig. 8(a) shows only the programmed applied forces. A noise force of magnitude 2 units is applied at (2, 0, 0). The forces shown in Fig. 8(b) and 9(a) are the resultant of the programmed force and noise force as seen by the F/T sensor placed at (0, 0, 0). Force diagrams were constructed by calculating the moments about X, Y and Z axes.

$$f_x = F \sin\alpha \cos\beta$$

$$f_y = F \sin\alpha \sin\beta$$

$$f_z = F \cos\alpha$$

and

$$T_x = f_z \times dy - f_y \times dz$$

$$T_y = f_z \times dx - f_x \times dz$$

$$T_z = f_y \times dx - f_x \times dz$$

Where, T_x, T_y and T_z are torques about X, Y and Z axes respectively. F is the force vector passing through the point (dx, dy, dz) with respect to O(XYZ) and f_x, f_y and f_z are the force components of F along the principal axes. α is the angle between the force vector F and the Z axis. β is the angle between the projected F in the XY-plane and the X axis.

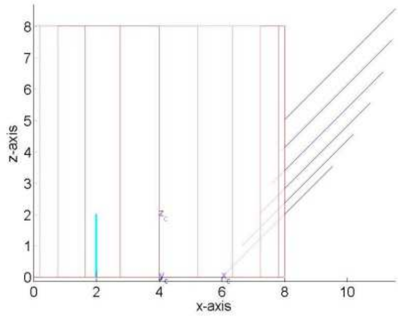


Fig. 8(a): (Color online) Oblique forces with Z-directional disturbance

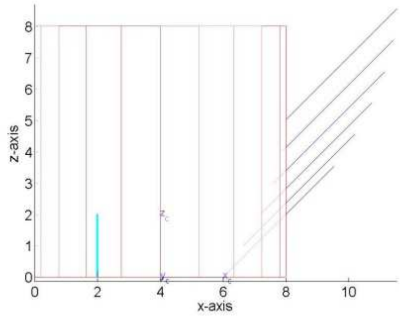


Fig. 8(b): (Color online) Total forces after superimposing vertical disturbance

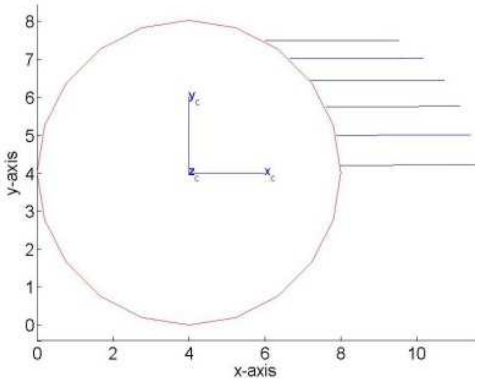


Fig. 9(a): (Color online) Oblique programmed forces on curved surface

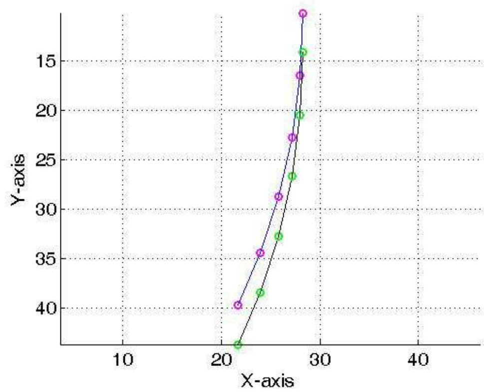


Fig. 9(b) : (Color online) Desired force diagram with green markers and actual one with magenta markers

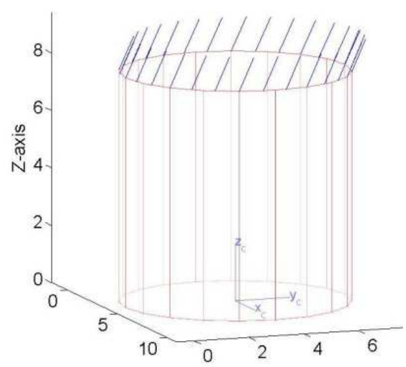


Fig. 10(a): (Color online) Programmed circumferential forces

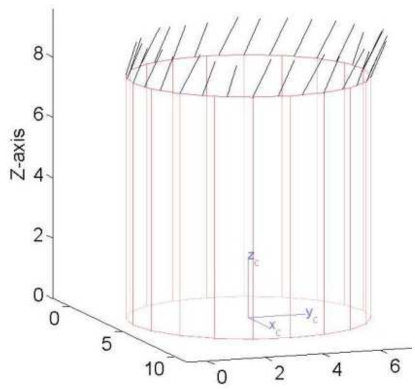


Fig. 10(b): (Color online) Noisy circumferential forces

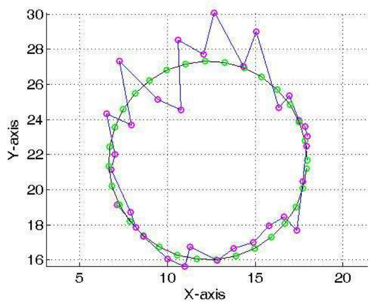


Fig. 11(a): (Color online) XY view of Force diagrams of desired & actual force trajectory

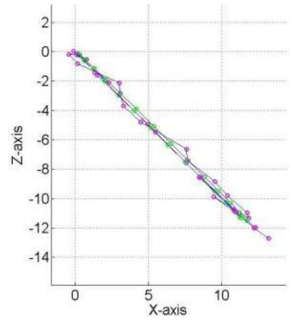


Fig. 11(b): (Color online) XZ view of Force diagrams of desired & actual force trajectory

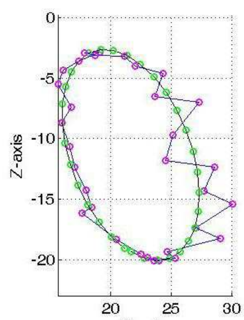


Fig. 11(c): (Color online) YZ view of Force diagrams of desired & actual force trajectory

The noise force, F_{noise} and torque, T_{noise} are superimposed on the programmed force. In fig. 10, the line with green markers shows the expected force diagram for the programmed forces. The blue line with magenta markers shows the actual force diagram obtained after superimposing the noise force. It can be seen that the graph with noisy forces is shifted in Y-direction proportional to noise force component, which is due to the noise added in Z-direction at point (2, 0, 0). The shape of the force diagram resembles the positional contour traversed by the robot.

Simulation of the contact mode operation along the circumference of the top face of the cylinder is conducted. Fig. 10(a) and (b) show force generated during programmed contact mode operation and contact mode force superimposed by force disturbance respectively. For simulating noise disturbance, random noise, F_{noise} (Φ,Ψ), was added to the applied forces. Here F_{noise} is the magnitude of the noise force vector and Φ and Ψ are the angles made by it with Z and projected noise force in XY plane and X axis, respectively.

Figs. 11(a), (b) and (c) are the force diagrams obtained by plotting torques with respect to O(XYZ), where the sensor is located. The desired force trajectory is shown with green markers in force diagrams and the actual noisy trajectory is shown with magenta markers. The noise forces are generated with random number generator with variance 0.01. Figs. 11(a), (b) and (c) show different views of the force diagram. The distortion of the force diagram due to random noise can be clearly seen in the graph with magenta markers. It can be seen that the force diagram viewed normal to X-Y plane shows the circular contour traversed by the robot. In Fig. 11(b), the force diagram orientation seen is due to the angular orientation of the programmed force.

IV. Remote Manipulation with Intermediary Telepresence

Contact perception has always been a very challenging component in telepresence. Haptic solutions are available. But these haptic solutions come with elaborate physical systems at both remote and master site and hence not warranted and not feasible for many of the situations. The haptic solutions greatly suffer from objectivity, therefore may result in inconsistency in operator's role. Intermediary telepresence instead is the visual communication of the remote site operations so as to handle remote contact manipulation accurately. Fig. 12 shows that the trajectory commanded at the master site and the path followed by the slave at the slave site. The commanded trajectory and the path following feedback were updated in real time both in Wm and Ws. A radial distance of 1 mm separates the concentric circles in Fig. 12. The width of the line (thickness of the pen tip) is measured to be 220 microns. The resolution of the 6 axis force-Torque sensor used in the experiments is 0.0025N.

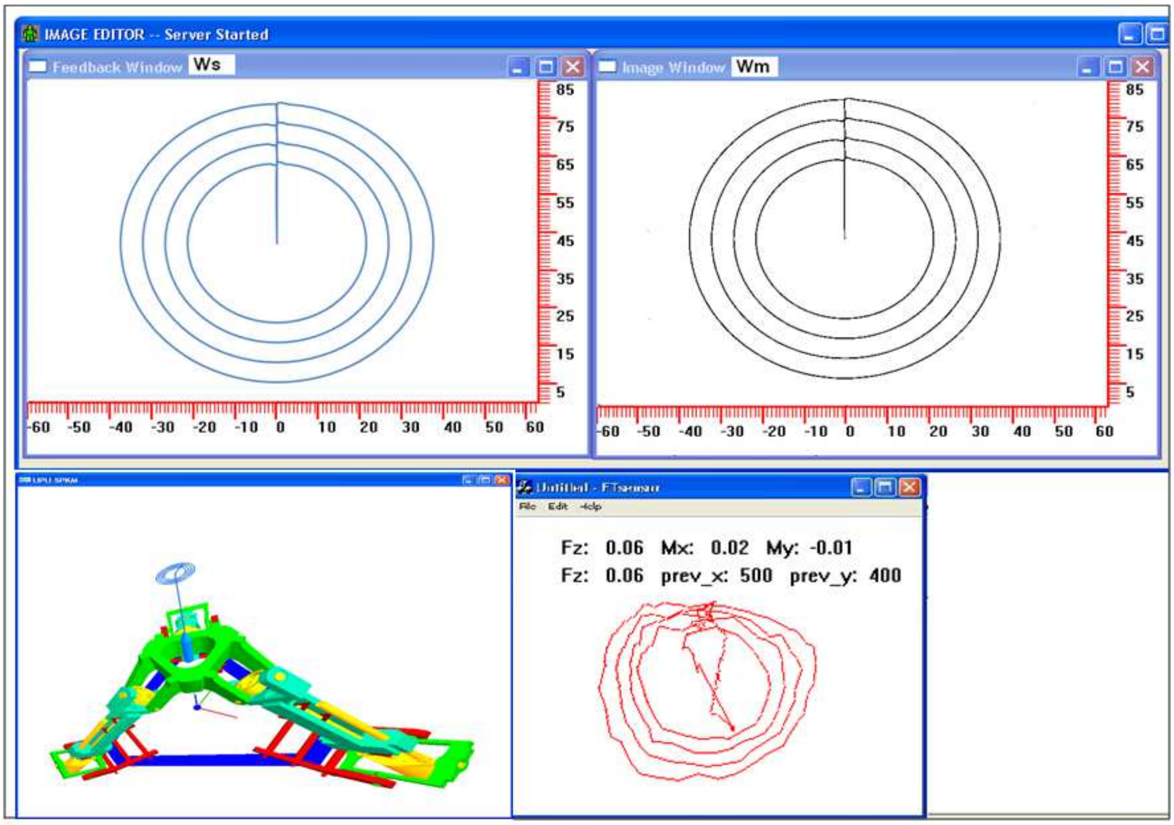


Fig. 12: (Color online) Master screen depicting the trajectory commanded at the master site and the path followed by the 3-UPU (Universal-Prismatic-Universal) manipulator slave along with 3D visualization of the slave and force diagram in force feedback window

In addition to the task space trajectory, the graphic simulator duplicates the motion of the slave in real time. The operator at the master site can visualize the slave manipulator linkage motions through real time graphic simulator visual display. Force feedback is an important component of telepresence. Camera or 3D display of mechanism would not be able to perceive forces acting at the interface of the tool and the job. In case of remote operations, monitoring the force field at slave site setup is very important. Force diagrams constructed using multiple components of wrench information are found to be highly effective. The real time force field feedback at the bottom right is displayed on the master screen (see fig. 12). It can be seen that the force diagram can be designed to present minute details of the wrench interaction of the end effector with the environment. The visible small disturbances in force window at particular location of the diagram are due to change in accelerations because of change in direction of the trajectory. This would enable the operator to monitor the force interactions between the tool tip and the environment.

V. CONCLUSIONS

A research on interpretation of wrench to aid remote manipulation is presented. Wrench space analysis is presented. It is shown that the force diagrams are very useful feature for intermediary telepresence. The diagrams not only indicate the local forces encountered by the environment but it gives a global view of the forces that are appearing on the work table. Monitoring of the force diagram can enhance the operator knowledge about contact wrenches, real time force trajectory, the accuracy of the motion and force trajectory and the state of the remote site in terms of wrench state. Several experiments are presented to substantiate the usefulness of the feature.

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