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HAPTIC INTERFACE FOR FORCE/MOTION CONTROLLED MOBILE MANIPULATOR

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Abstract: The experiment shows how a robotic platform with force and motion control capabilities, coupled with a haptic device, could be of significant improvement to an industrial task. Shown here is a task involving a polishing job of an aircraft canopy with unknown surface. This paper proposed leaving the low level task of maintaining constant contact force and good compliance to the canopy surface to the robot, while keeping the high level intelligence to be provided by the human. This is done by connecting the force/motion capabilities of the robot to the human operator through a haptic interface. The resulting setup enabled the haptic device to reflect the contour of the surface that was in contact of the manipulator, while the manipulator performed a force control task. Stiffness of the surface was made an indicator to the performance of the force control.

Keywords: Operational space haptics compliant deskilling force motion control

1. INTRODUCTION

The application of the haptic interface has expanded into various areas, such as medical and robotic teleoperation to teaching aid and exploration of virtual and nano environment.

A lot of study has been made in the various design of haptic interfaces, such as the PHANToM (Massie and Salisbury, 1994), Delta-mechanism-based haptic device (Grange *et al.*, 2001) (Tsumaki *et al.*, 1998), and other designs such as ((Berkelman *et al.*, 1999), (Yoshikawa and Nagura, 1997)) to name a few. Other efforts are in the development of realistic haptic rendering to the user, such as in (Okamura and Cutkosky, 1999) and (Hayward and Astley, 1996), In our paper, we present an application example of integrating haptic interface into an existing robotic platform in a telerobotic task. The main idea is to incorporate haptic device into a telerobotic system to improve the performance and at the same time create a closer and more realistic interaction between the human operator and the machine. An example of such effort can be found in (Maneewarn and Hannaford, 1998), who used the haptic device in telerobotics to avoid singularities. As the user approaches singularity while operating the robot with the haptic device, he or she will feel a force pushing away from the singular region.

In our experiment, we attempt to use the haptic device on the existing mobile robotic manipulation platform to improve its performance in an industrial task. Having developed a robotic platform with unified force and motion control, we would

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like to be able to interact with the environment by the use of the haptic interface.

In the conventional way, the manipulator would be in motion control, receiving its desired position command from the haptic device, which is held by the user. A force/torque sensor is mounted at the end-effector and the contact forces of the end-effector with the environment is sent back to be displayed by the haptic device. In this method, all the degrees of freedom (DOFs) of the robot are in motion control. As the user pushes on the haptic device, the robot reflects this motion by moving in the respective directions. If it was in contact with a surface, then the contact force will be read by the force/torque sensor and displayed on the haptic device. This reflected force will be dependent on how hard the user pushes and the stiffness of the surface.

In our platform, a unified motion and force control has been implemented with operational space formulation (Khatib, 1987). This means that the end-effector is in motion control in certain directions, and in force control in others. Those DOFs in force control would perform a task of maintaining a contact force with the environment following a desired force-time trajectory. In this case, the haptic device which sends motion control command to the manipulator would not be in control of these directions. Furthermore, the contact forces with the environment, being controlled, would no longer be the resulting interaction between the human-controlled robot with the environment, but the result of a given desired contact force with the surrounding.

In utilizing the haptic device in this application, displaying the desired contact force between the end-effector and the environment does not provide any new information to the user. We propose to set the manipulator to return the position of operational point of the end-effector to be displayed by the haptic device. As a certain contact force is maintained between the end-effector and the environment, a compliant behavior would result as the end-effector is commanded to move in the motion control axes. This means that the end-effector would trace the contour of the surface while maintaining the desired force. When the position of the end-effector is fed back to the haptic device and a control loop is closed, the surface contour would be reflected as a virtual surface to the human operator. Our idea is described by Figure 1.

A spring-damper model was used to simulate the constraints at the haptic interface. The spring and damping coefficients can also be used to give an indication of how well the force control process is at the end-effector. They can be made to vary with

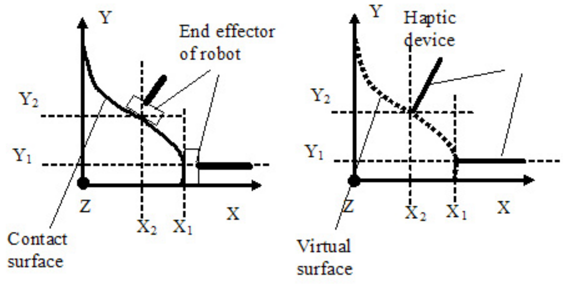

Fig. 1. Example of the setup in a planar robot. Translation in Y of the planar robot is in motion control while translation in X and rotation in Z are in force control. Motion of haptic in Y (from Y_1 to Y_2) is reflected at the robot which traces the surface and maintain compliance with force and moment control. Resulting position in X (from X_1 to X_2) and rotation of Z is fed back to be reflected by the haptic.

the error in force control, thus providing extra information.

The scheme was implemented onto a robotic platform of PUMA 560 with a task of polishing an aircraft canopy, as described in (Jamisola *et al.*, 2002). In this task, the robot is set to maintain a constant force perpendicular to the surface of the aircraft canopy. The contour of the canopy is not known to the robot, therefore compliant motion (moment control) was necessary in performing the task. When the system is integrated with a haptic device, the human operator will direct the end-effector, while the robot will assist in exerting a stable and constant polishing force. The contact surface and the error of the force control process are displayed at the haptic device. The haptic device used is the 6 DOF PHANToM, model 1.5A, with 3 DOF force feedback. The haptic device communicates with the robot via 100 Mb/s TCP/IP.

This setup is also an example of the decoupling of skill and intelligence in the execution of a task. As it is generally accepted that higher levels of intelligence is very difficult to program into a robot, we can assign the lower level of the task to the robot, and the higher level of intelligence to a human operator through the haptic device. We refer to this as 'deskilling' of human operator as we can now transfer the skill of performing a manual task to the robot, while the human operator holds the intelligence for the task. This is desirable as skills in performing manual jobs could take years of practice to develop. In this idea, haptics is the crucial enabling factor as the operator will directly drive the manipulator and come into 'direct' contact with the environment, thus creating a close involvement of the operator with the task, while the robot control algorithm takes care of lower level intelligence, such as the maintaining of a stable and constant force normal to the surface being polished.

The following sections give a brief background on the control scheme used (the operational space formulation) and the integration of the haptic device into the existing control scheme. The experiment and the result are then presented and discussed.

2. HAPTIC INTERFACE ON OPERATIONAL SPACE FORMULATION

2.1 Operational Space Formulation

Operational Space formulation (Khatib, 1987) is a control approach where the robot dynamics is expressed in operational space (Cartesian space as seen from the end-effector or tool). The desired motion and contact forces are then incorporated into force commands at the task level. These commands together with the robot dynamics in operational space are then used to compute the required joint torques which are sent directly to the torque-controlled joint motors.

In operational space formulation, the total force $\mathbf{F}$ is a combination of the force for free motion (position control) and force for constrained motion (force control). To achieve unified approach for end-effector dynamic decoupling, the control structure selected is as shown in Equation 1.

$$\mathbf{F} = \mathbf{F}_{motion} + \mathbf{F}_{force} \tag{1}$$

where

$$\begin{aligned} \mathbf{F}_{motion} &= \hat{\Lambda}(\mathbf{x})\Omega\mathbf{F}^*_{motion} + \hat{\boldsymbol{\mu}}(\mathbf{x},\vartheta) + \hat{\mathbf{p}}(\mathbf{x}) \\ \mathbf{F}_{force} &= \hat{\Lambda}(\mathbf{x})\bar{\Omega}\mathbf{F}^*_{force} + \mathbf{F}_{sensor} \end{aligned} \tag{2}$$

where Ω and $\bar{\Omega}$ are the selection matrices to specify operational space directions that are force and motion controlled. The matrices $\hat{\Lambda}$, $\hat{\mu}$ and $\hat{p}$ are the estimates of the inertia matrix, Coriolis and Centrifugal matrices, and gravity vector, as seen from the operational space (Khatib, 1987). $\mathbf{F}^*_{motion}$ and $\mathbf{F}^*_{force}$ are the forces before dynamic compensation.

It is then converted to joint torques by

$$\mathbf{\Gamma} = J^T\mathbf{F} \tag{3}$$

where $\mathbf{\Gamma}$ is the joint torque command to be sent to the joint motor and J is the manipulator Jacobian in operational space.

2.2 Integration with the Haptic Device

The use of the operational space formulation enables the manipulator to operate in motion and/or force control. When certain axes are set in force (or moment) control, instead of displaying the contact forces between the end-effector and the environment, the haptic device will reflect the position of the end-effector in tracing the surface being polished. This is because the contact forces would not be reflecting the interaction between the human operator (through the haptic device and the robot) with the environment. Instead it will be of a specified desired force-time trajectory that has been specified by the task for the robot to follow.

This setup causes the robot and the haptic device to have behave in exactly the same manner, just in the opposite direction of command flow. The motion control command in the form of position vector from the user is sent by the haptic device to the motion-controlled axes of the robot. The end-effector position resulting from the the compliant motion and the reaction between the end-effector and the environment (also in the form of position vector) is sent in the opposite direction to the haptic device to be displayed. A control loop is setup at the haptic side to generate force command to satisfy the position constraints in the DOFs that are force-controlled by the manipulator.

Generation of force/moment command to drive or constrain the haptic device operation point to the desired position and orientation can be done using a spring damper model such that:

$$\begin{aligned} \mathbf{F}(\mathbf{x}) &= -k_f(\mathbf{x} - \mathbf{x}_c) - b_f\dot{\mathbf{x}} \\ \mathbf{M}(\mathbf{x}) &= -k_m\delta\mathbf{\Phi} - b_m\omega \end{aligned} \tag{4}$$

where $\mathbf{F}$ and $\mathbf{M}$ are the force and moment command to be sent to the haptic device, $\mathbf{x}$ is the position of the haptic operating point, $\mathbf{x}_c$ is the desired position of the constraint, representing the unknown surface being traced by the end-effector, and $\dot{\mathbf{x}}$ and ω are the linear and angular velocity. $\delta\mathbf{\Phi}$ is the instantaneous angular error between the actual orientation of the haptic device and the desired orientation, which is the orientation of the robot's end-effector.

$$\delta\mathbf{\Phi} = -\frac{1}{2}(\hat{\mathbf{s}}_1\mathbf{s}_{1d} + \hat{\mathbf{s}}_2\mathbf{s}_{2d} + \hat{\mathbf{s}}_3\mathbf{s}_{3d}) \tag{5}$$

where $\hat{\mathbf{s}}_1$, $\hat{\mathbf{s}}_2$, $\hat{\mathbf{s}}_3$ and $\mathbf{s}_{1d}$, $\mathbf{s}_{2d}$, $\mathbf{s}_{3d}$ are the three columns of the rotation matrix representing the actual and the desired orientation of the haptic device.

The spring damper model above would constrain the haptic operational point on both sides with the spring damper system. In the application of polishing, since we will be in contact with a surface, it is necessary to create a one sided spring-damper constraint. The spring-damper model can be modelled as:

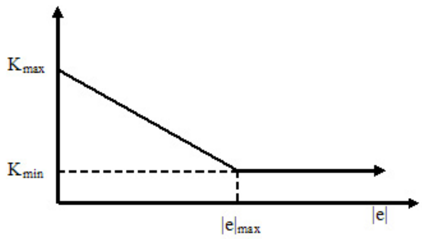

Fig. 2. The stiffness of the virtual surface as a function of (absolute value) of the force error.

$$\mathbf{F}(\mathbf{x}) = \begin{cases} -k_f(\mathbf{x} - \mathbf{x}_c) - b_f\dot{\mathbf{x}} & ; x \leq x_c \\ 0 & ; x > x_c \end{cases} \tag{6}$$

The spring and damping coefficients can also be made to reflect the error in the force control process, such that:

$$k(e) = \begin{cases} (K_{max} - K_{min})|e| + K_{min} & ; e \leq e_{max} \\ K_{min} & ; e > e_{max} \end{cases} \tag{7}$$

as shown in Figure 2.

In this way, the stiffness of the virtual surface described by the haptic device would be bound within K_{max} and K_{min}. When error in the force control process is zero, the stiffness of the virtual surface is maximum. When the error is at or beyond the threshold e_{max}, then the stiffness of the surface is minimum at constant K_{min}. This would prevent the coefficients from going into zero or negative values.

3. TELEOPERATION EXPERIMENT

The experiment was carried out on a PUMA 560 manipulator platform in operational space formulation. The industrial application of polishing an unknown surface requires a constant force to be exerted normal to the surface. This requires polishing tool at the end-effector of the manipulator to comply with the surface.

The 6 DOFs of the manipulator are divided into motion and force control. Motion are controlled in the X and Y translation of the Base Frame $\{\mathcal{O}\}$ and the rotation around Z axis of the Tool Frame $\{\mathcal{T}\}$ (see Figure 3). Force controlled axes are the force along Z axis of the Tool Frame (to be maintained at 10 N) and moment around X and Y axes of the Tool Frame (to be maintained at 0). Maintaining the moment around X and Y axes of the Tool Frame at 0 creates the compliant motion of the tool to the surface being polished.

The position commands, in the X and Y translation of the Base Frame, are given by the user through the haptic device. The rotation around the Z axis of the Tool Frame is locked at zero. The

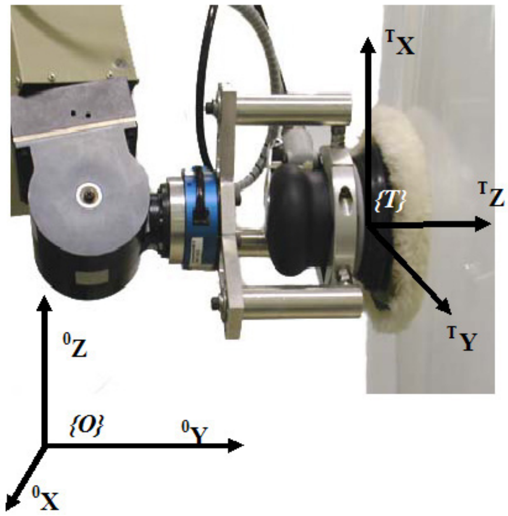

Fig. 3. Frame Assignment of the Base Frame $\mathcal{O}$ and Tool Frame $\mathcal{T}$

manipulator takes care of the low level tasks such as path planning and force and motion control. As mentioned in section 2, the resulting end-effector position as it traces the surface being polished is reflected at the haptic device. The result of the experiment is given in section 4.

In this experiment, a pneumatic polishing tool is utilized. This also introduces vibration (noise) as it spins at approximately 1000rpm upon 10N contact force with the canopy. The haptic device used in the experiment is a 6 DOF PHANToM, model 1.5A, with 3 motorized joints. Therefore, it can only display 3 DOFs of force feedback.

The threshold error e_{max} in maintaining constant force (as in Equation 7) was set to be at 30% of the desired value. That means force control error beyond 30% of the desired value would have induce the same stiffness at the virtual surface.

It is also interesting to compare the effectiveness of the system in performing polishing job as compared to human operators. Conventionally, a human operator would physically hold the polishing tool and polish the canopy. This is to be compared with our setup using the robot and the haptic device where the low level portion of the task is taken care of by the robot (in maintaining the constant force and complying with the surface curvature). The human operator, however, provides the high level intelligence of supervising the task, spotting any defects on the surface being polished and at the same time, still be able to have the kinesthetic feel of the job.

4. RESULT

Because the PHANToM haptic device that we used has only 3 DOF force feedback, it was

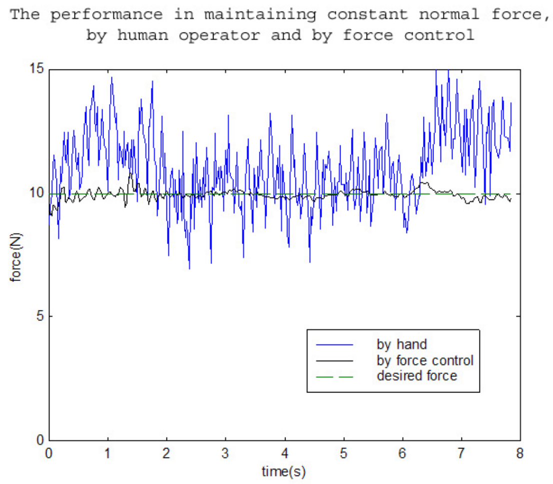

Fig. 5. The performance of maintaining constant force of 10N, when it is polishing tool is held by human operator compared to that by force control by the robot. The high frequency noise is from the spinning of the polishing tool, which is more prominent when the tool was held by human operator.

not able to reflect the orientation of the end-effector (and the polishing tool) on the haptic. However, the user was able to trace a virtual surface representative of the shape of the canopy being polished, while the normal contact force was being maintained at 10N (Figure 4).

Figure 5 shows the performance of the setup in force control as compared to a human operator. The system was found to be effective in maintaining the constant force and in compensating for the disturbance caused by the spinning of the pneumatic polishing tool. The error was found to be within $\pm$ 2 Newton from the desired value of 10N. Stiffness of the virtual surface displayed by the haptic device was an indication of the error.

It should be noted that during this experiment, the human operator was given a visual feedback of the contact force reading and therefore was able to track the contact force close to 10 N. Performing the task with purely kinesthetic feel, without visual feedback was found to be very difficult and error could vary to a few hundred percent. In a conventional application, the operator does not have a visual reading feedback and rely entirely on the feel and years of practice to polish an aircraft canopy to an acceptable level.

The compliant motion was found to be comparable to that of a human operator, if not better due to the better compensation against the disturbance from the spinning polishing tool (Figure 6).

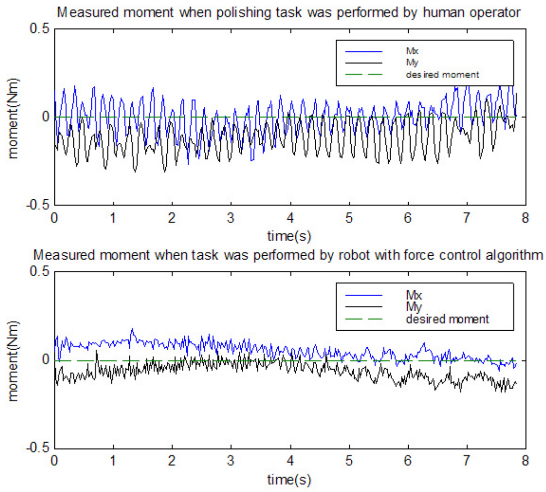

Fig. 6. Comparison on the compliant motion showed a comparable result when the task is executed by human operator and by robot. Zero measured moment around X and Y axis of the tool frame shows perfect compliant of the polishing tool to the unknown contact surface. Vibration noise is more visible at human operation.

5. CONCLUSION

The experiment shows how a robotic platform with force and motion control capabilities, coupled with a haptic device, could be of significant improvement to an industrial task. Robots are superior to human in low level jobs such as accurate trajectory tracking and steady force tracking. High level of intelligence was easily provided by human through the haptic device, which acts doubly as an input device and a feedback device.

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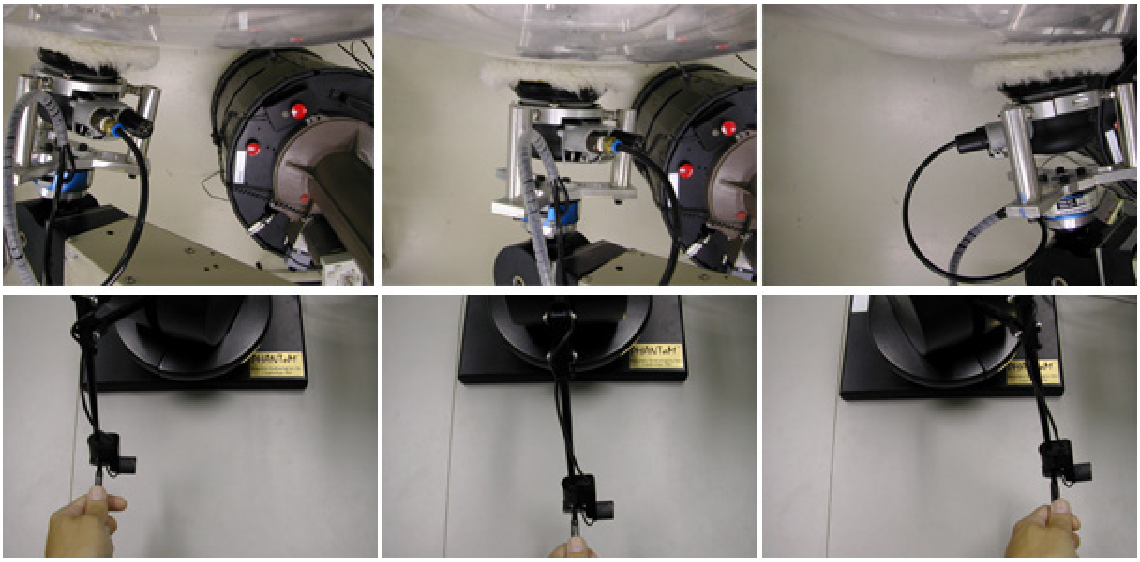

Fig. 4. The compliance at the manipulator side is reflected on the haptic side, while the manipulator maintains 10N constant force normal to the surface of the aircraft canopy.

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