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# Preliminary Study of Virtual Nonholonomic Constraints for Time-Delayed Teleoperation

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***Abstract*— Direct teleoperation with multisecond time-delayed telemetry between master and slave is challenging for humans to perform. When controlling a holonomic robot with many degrees of freedom, operators may incidentally provide commands in an intended direction without realizing their mistake until receiving feedback several seconds later. For some applications, imposing a virtual nonholonomic constraint (VNHC) on the motion of the end effector can help prevent operators from moving in an unintended direction by reducing the number of controllable degrees of freedom. This paper presents the development of a VNHC for a planar time-delayed telerobotic task, motivated by an on-orbit telerobotic satellite servicing operation. We also describe a nonholonomic virtual fixture (NHVF) that adheres to the VNHC to further reduce the potential for operators to input mistaken commands. We report the results of a pilot study in which teleoperation with a VNHC was found to have comparable task performance to holonomic planar teleoperation, while decreasing operator workload. The NHVF was found to decrease performance slightly, though user feedback indicated that a differently implemented virtual fixture and controller may improve performance.**

## I. INTRODUCTION

The challenges of teleoperation with large time-delayed telemetry between master and slave are well-established. In 1965, Ferrell first observed that in the presence of significant time delay (more than several hundred milliseconds), human operators adopt a "move-and-wait" strategy to avoid stability issues [1]. After performing an action, operators will wait the length of the total system delay to receive feedback about the resulting error between the desired and actual outcome of the previous action. This problem can be acute in the context of on-orbit telerobotic servicing of spacecraft, with human operators on earth remotely controlling satellite intervention operations on-orbit, in which the round-trip telemetry delays are commonly several seconds or more.

In a telerobotic satellite refueling mission scenario, multi-layer insulation (MLI) (a thermally protective blanket covering the satellite exterior) must be bypassed to gain access to satellite fuel port. This can be accomplished by cutting seams of tape adhering overlapping sections of MLI and folding back a portion of the MLI to expose the port. The specular MLI flexes and deforms when in contact with the robot's end effector, making this task difficult to perform with precision, particularly in the presence of time delay.

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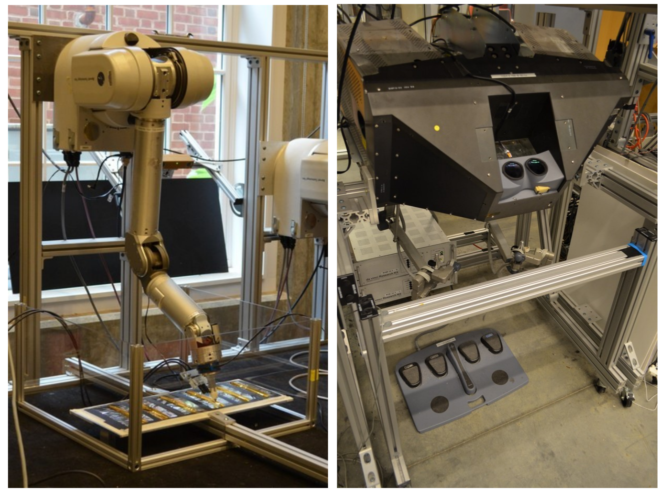

Fig. 1: A Barrett WAM Arm (left) slave robot shown with the test blanket setup. The right-hand master controller of a da Vinci Research Kit (right) is used to teleoperate the WAM's end effector.

It is possible to exploit the constraints of the task to make the cutting process easier for the teleoperator, using a task model framework [2]. In this application, the MLI cutting operation is structured such that the motion of the crescent-shaped cutting blade attached to the robot's end effector can be constrained to the plane of the MLI surface. Thus, a full 6 degree of freedom task is reduced to a 3 DoF planar task.

In previous studies [3], we observed that users often provided unintentional commands in the lateral (non-cutting) direction during planar control of the cutter. Operators were unaware that they had given this incidental command until after the total loop delay had elapsed. They then had to try to correct their lateral position with an open-loop command in the subsequent motion.

Lateral cutter motion cannot be eliminated entirely, as the blade must be able to avoid obstacles such as tape rips, wires, and screws. However we wish to reduce or eliminate unintentional motion by applying our understanding of the task, noting that the primary motion of the end effector is longitudinally along the tape seam. This motivates the use of an artificial constraint on the motion of the cutter.

The introduction of a virtual (*i.e.,* software-imposed) nonholonomic constraint on the cutter path can reduce the number of input degrees of freedom while maintaining the total degrees of freedom of the end effector. Further, if the desired cutting path for the end effector is known, we can implement a virtual fixture subject to the nonholonomic constraint by automatically governing one of the remaining degrees of freedom while still keeping the human operator in direct control.

The three main contributions of this paper are as follows: First, we introduce the concept of a virtual nonholonomic constraint (VNHC) that assists human operators by reducing the number of degrees of freedom that can be commanded to a teleoperated robot, thereby reducing a source of error in the teleoperation process. Second, we extend the concept of the VNHC to include a nonholonomic virtual fixture (NHVF), which is a soft virtual fixture that adheres to a VNHC. Third, we report the implementation and preliminary experimental performance evaluation of both VNHC and NHVF for the planar time-delayed teleoperation task of MLI tape cutting.

The remainder of this paper is organized as follows: Section II reviews related prior work on time-delayed space teleoperation, artificial nonholonomic constraints, and virtual fixtures. Section III describes the technical approach for the VNHC and NHVF. Sections IV and V report the experimental setup and experimental results of a pilot user study. Section VI summarizes the conclusions.

## II. BACKGROUND AND RELATED WORK

The general problem of telemanipulation has been the subject of extensive research for over 60 years [4]. Sheridan and Ferrell first articulated the specific problems arising in telemanipulation over telemetry channels with significant time delay, motivated by the needs of the US space program in the early 1960s [5].

Many approaches exist to alleviate some of the issues with time-delayed teleoperation. For direct teleoperation, these strategies focus on maintaining stability of bilateral force feedback under time delay [4]. However, such approaches are limited in practical applicability for systems having delays greater than several hundred milliseconds, due to the "move-and-wait" behavior employed by teleoperators [1].

For tasks in which the remote manipulation task can be accurately simulated, predictive augmented reality displays have also been shown to assist with time-delayed teleoperation [6]–[9]. Predictive displays and force feedback can extrapolate the current system state forward in time to provide advanced feedback to the operator, but such extrapolations require an accurate model of the remote robot's interactions with the remote environment. Supervisory control, in which the operator gives high-level commands to the remote robot rather than directly teleoperating the arm, can also help alleviate some of the problems associated with time delay. However, this approach can be problematic in unstructured environments.

The VNHC and NHVF approaches described in this work differ from that reported in a rich body of literature from a decade ago on "collaborative robots" or "cobots", originally proposed by Peshkin and Colgate [10]–[12], which engage in direct physical interaction with a human user, employing computer-controlled continuously variable transmissions and "steerable" nonholonomic joints to constrain motion to a single degree-of-freedom within a higher dimensional task space. In constrast, the approach employed herein uses active software-controlled virtual fixtures that both guide the user-controlled remote tool toward the task location, and also provide guidance to maintain the correct path to accomplish the MLI-cutting task.

In [13], Takubo *et al* report a robot assistant system to enable a human operator to manipulate large three-dimensional objects by imposing an artificial nonholonomic constraint that constrains its motion as if it were equipped with fixed wheels.

Prior work on teleoperated on-orbit satellite servicing operations has not focused on tasks involving telerobotic interaction with flexible, deformable materials such as MLI blankets. Hummel [14] reported a multi-user study to investigate operator performance using several different control methods for an MLI-manipulation task. However, the task was performed in simulation, and there was no time delay in the system.

In our previous studies, we investigated the impact of implementing a planar virtual fixture with force control for a time-delayed teleoperation task based on a satellite refueling mission scenario [2], [3], [15]. In this task, operators were required to utilize a master-slave teleoperation system to cut a section of tape adhering overlapping sections of the MLI on a mock satellite panel using a seam-ripper-like cutting blade. Simple virtual fixtures were shown to improve teleoperation performance in the presence of telemetry time delays [2]. Force control in the axis normal to the plane was observed to improve cut quality and reduced operator workload by regulating an additional component of the end effector's position [3].

## III. TECHNICAL APPROACH

The general cutting strategy employed is to restrict motion of the cutter to the 2D plane of the satellite panel surface, based on the task model for the cutting operation. The operator controls motion in the $x$-$y$ plane, while the slave robot applies a constant "downward" force (into the surface) along the $z$ axis. Figure 2 shows a photograph of the cutting setup as well as our coordinate system convention. In this strategy, the approach vector ($z$) must be approximately aligned with the surface normal, so rotations about the $x$ and $y$ axes (*i.e.*, roll and pitch) are prohibited. Rotation about the $z$ axis (*i.e.*, rotation in the $x$-$y$ plane) is allowed.

The seam to be cut consists of mostly straight line segments on a plane, so it is natural to consider virtual fixture constraints to assist the teleoperator. In our prior work, we implemented both plane and line virtual fixture constraints on the teleoperation master [15]. While a line virtual fixture would seem to be the most appropriate for cutting along a straight edge, it can sometimes be too constraining because the virtual fixture line must be correctly registered to the actual tape seam, and because cutting anomalies such as bunching or tearing of the tape may require the operator to stray from the line. This motivates consideration of a soft virtual fixture, where motions away from the preferred

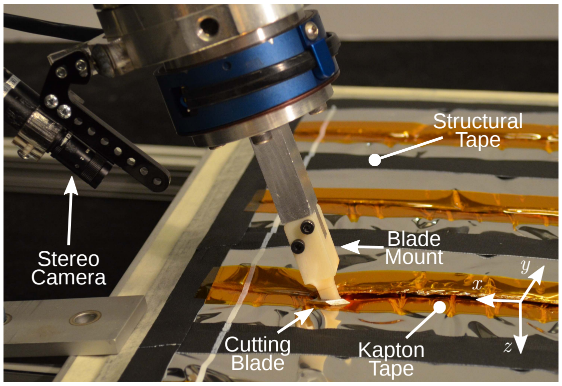


Fig. 2: Cutting test setup used in the pilot study.

direction (in this case, motions away from the line), are allowed but require more effort [16].

In contrast, the plane virtual fixture does not constrain motion along the plane at all; in fact, the plane normal only specifies the direction of force control [2]. However, without constraints within the plane, operators can inadvertently command the cutter laterally along an unintended path.

The above observations led to the two concepts presented in this paper, which are discussed in further detail below:

1) A virtual (software-imposed) nonholonomic constraint (VNHC) that reduces the number of inputs the operator has to provide to the cutter while maintaining the ability to reach all possible positions and orientations in the virtual plane.
2) A nonholonomic virtual fixture (NHVF), which is a soft virtual fixture that guides the operator to steer the cutter back to the reference line subject to the virtual nonholonomic constraint (VNHC).

### A. Nonholonomic Constraints

A nonholonomic robotic system has fewer controllable degrees of freedom than total system degrees of freedom. Nonholonomic systems can be difficult to teleoperate, as users must map the control commands to the desired output states. In general, prior literature has focused on providing Cartesian control inputs to nonholonomic systems [17]–[19], rather than the inverse problem.

However, for the motivating application of planar tape cutting under time delay, the difficulty of commanding three degrees of freedom could potentially be mitigated by reducing the number of inputs to the system, particularly because there is no requirement to move instantaneously in a lateral direction. By selecting a familiar nonholonomic constraint, such as one similar to driving a car, a natural mapping from input to output space can be achieved. Additionally, the overall path of the tape-cutting operation is more important than precise location of the cutter, so operators would not be required to "parallel park" the cutter to achieve a specific position and orientation.

A nonholonomic system has a potential advantage over a holonomic system configured such that only a subset of the input dimensions are controlled simultaneously (*e.g.*, switching between lateral and longitudinal control modes) because a steerable system can be continuously controlled.

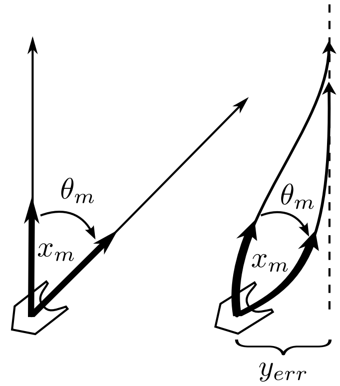


Fig. 3: Schematic drawing illustrating the system behavior under the VNHC (left) and NHVF (right) before and after an angular input $\theta_m$. The bold arrow represents a forward input $x_m$, and the thin arrow represents the continuation of the path with no further angular input. The dashed line represents the virtual fixture.

### B. Unicycle Virtual Nonholonomic Constraint

The nature of the cutting task lends itself to nonholonomic constraints arising from rolling without slipping on a plane, such as a car or bicycle model. We choose to base our virtual nonholonomic constraint on a unicycle (also referred to as a rolling wheel), as it is simple, intuitive, and the steering angle can be controlled independently from the planar position. The constraints for a unicycle are given by [20]:

$$\begin{aligned} \dot{x} - r\dot{\phi}\cos\theta = 0 \\ \dot{y} - r\dot{\phi}\sin\theta = 0 \end{aligned} \tag{1}$$

where $x$ and $y$ are the Cartesian position of the center of the wheel, $\theta$ is the heading angle, $r$ is the radius of the wheel, and $\dot{\phi}$ is the angular velocity about the wheel's center. The forward speed of the wheel can be given as $v = r\dot{\phi}$. We can apply this constraint directly to the planar model of the cutting blade to impose the unicycle constraint on the end effector. The motion of the cutter is then controlled directly by the operator, who provides the desired velocity, $v = \dot{x}_m$, and steering angle, $\theta = \theta_m$ via an input device.

### C. Soft Virtual Fixture with Nonholonomic Constraint

If a desired straight-line path for the cutter is known *a priori*, it is straightforward to implement a controller to steer the cutter towards that line. For this tape-cutting application, we can define a virtual fixture at the seam where the two layers of insulation overlap. A simple PD controller then determines a cutter angle ($\theta_{PD}$) based on the lateral error ($y_{err} = y - y_{VF}$) of the cutter, where $y_{VF}$ is the lateral position of the virtual fixture line in the cutting plane:

$$\theta_{PD} = K_p y_{err} + K_d \dot{y}_{err} \tag{2}$$

The motion of the cutter is then controlled from position commands $x_m$ and $\theta_m$ as:

$$\begin{aligned} v &= \dot{x}_m \\ \theta &= \theta_m + \dot{x}_m \theta_{PD} \end{aligned} \tag{3}$$

Note that with no angular input from the operator, the cutter follows the PD controller's inputs to orient and align with the virtual fixture. The operator is able to override the cutting angle from the PD controller with the input $\theta_m$, thus making this a soft virtual fixture.

Example responses to user inputs for both the VNHC and NHVF are illustrated in Fig. 3.

## IV. USER STUDY

To investigate the effects of VNHCs and NHVFs on teleoperation performance in the presence of significant telemetry time-delays, we conducted a four-subject pilot study of the multilayer insulation (MLI) tape-cutting operation.

This section reports the experimental setup, the conditions tested, and the procedure used for the experiments and the data analysis.

### A. Test Setup

The experimental setup used in this pilot study is similar to that of [3], which investigated an MLI tape-cutting task with a planar virtual fixture. Cutting is performed with a titanium blade (NASA Goddard Space Flight Center) mounted on a 7-degree-of-freedom Whole Arm Manipulator (WAM) (Barrett Technology, Inc, Newton MA). A stereo camera is mounted to the wrist joint of the WAM, focused on the cutting blade. A six-axis force-torque sensor (JR3 Inc., Woodland, CA) mounted between the WAM wrist and cutting blade mount provides cutter contact force information and enables active force control in the direction normal to the MLI.

A 7-degree-of-freedom da Vinci master tool manipulator (MTM) from a da Vinci Research Kit (DVRK) [21] is used to command the slave robot. Stereo video feeds with augmented reality overlays generated with rviz [22] are displayed to the user through the DVRK's stereo video console. No haptic feedback is provided to the user. Figures 1 and 2 show photographs of the test setup.

The master robot is controlled using the ROS [22] and cisst/SAW [23] open-source robot software systems, while the slave robot is controlled using the Orocos Real Time Toolkit [24] and ROS. Communication between the master and slave robots, including video and data, is accomplished over a local area network via ROS messaging. An overview of the master-slave hybrid force/position control architecture is given in [2].

On-orbit remote teleoperation from Earth is subject to telemetry delays of several seconds or more for both uplink and downlink. This is due to RF signal time-of-flight propagation delays and encoding/decoding delays inherent in commonly utilized global-scale RF telemetry systems, such as NASA's advanced tracking and data relay satellite system (TDRS), which employ geostationary satellites as relays [25]. Since teleoperation performance is known to be independent of the delay location (*e.g.* uplink vs. downlink) [26], in our experiments the delay was implemented as a single 4 s delay in the upstream communications using a ROS message filter.

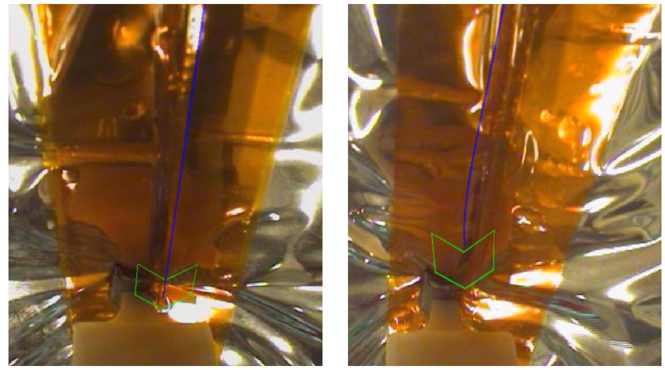

Fig. 4: Screenshots (cropped) of left stereo visualization used during the experiments, showing the cutter goal position (green chevron) and the path constraint (blue line) for the nonholonomic constraint (left) and nonholonomic virtual fixture (right) test conditions.

Mockup MLI blankets were constructed out of representative (but not space-qualified) industrial materials that closely resemble the physical properties of the space-qualified MLI materials commonly employed in satellites. The MLI blanket design and test fixture mounting is described in [3].

### B. Test Conditions

Four teleoperation approaches were evaluated. Prior studies have shown the benefits of force control used in conjunction with a planar virtual fixture for this specific task [3]. Thus, in all test conditions, the cutting plane is used as a virtual fixture to constrain the pitch and roll of the cutter with respect to the blanket, and force control is used in the planar normal direction to maintain a constant 4 N downward force on the blanket, as in our earlier work [2], [3].

For tasks in which the remote manipulation task can be accurately simulated, predictive augmented reality displays have also been shown to assist with time-delayed teleoperation [6]–[9]. For our cutting task, accurate simulation, and therefore predictive display, is not feasible because the cutting blade interacts dynamically with the flexible MLI. Instead, an augmented reality marker is used to indicate the goal position of the cutter as commanded by the user, rather than a predicted position.

The four test conditions are summarized as follows:

*1) Control:* The control test used the conditions as described above. The scaling between the master (MTM) and the slave (WAM) robots was $0.1$ for position commands (a 1 cm movement with the MTM resulted in a 1 mm movement on the slave) and $0.25$ for angular commands.

*2) Scaled Axes:* A second test condition implemented anisotropic position control. The longitudinal ($x$-axis) and angular input commands from the MTM were the same as the control test. However, the lateral ($y$-axis) commands from the MTM were scaled to 25 % of the lateral command (resulting a total scaling factor of $0.025$). This test condition represents a compromise between the control test and a full implementation of a VNHC.

*3) Nonholonomic Constraint:* In this condition, the motion of the cutter is limited to the unicycle nonholonomic constraint given in Eq. 1, with users commanding the forward and angular motion of the cutter, with the longitudinal and angular input commands from the MTM the same as in the control test. Note that this is equivalent to scaling the lateral axis to $0.0$. An augmented reality marker showing the constraint (in this case, a straight line projecting from the front of the cutter) was shown to the user in the master console, as shown in Fig. 4.

*4) Nonholonomic Virtual Fixture:* This test condition imposed a soft virtual fixture, subject to a VNHC. The line virtual fixture is defined by two points on the tape seam in the cutting plane, which are set manually by the experimenter prior to the trial. The input to the cutter command is given by Eq. 3, with an input scaling factor of $0.1$, such that a $1\,\text{cm}$ input to the MTM generates a $1\,\text{mm}$ motion of the cutter tip along the path. The heading angle control law is given by Eq. 2. The gains for the virtual fixture were tuned empirically to $K_p = 5\,\text{rad/m}$ and $K_d = 2\,\text{rad–s/m}$ and were constant throughout the trials. The constraint is displayed as an augmented reality overlay on the video screen, as shown in Fig. 4. The user can re-plan the path by changing the angle of the cutter, and subsequent motion will follow the new constraint.

### C. Procedure

The pilot tests were performed with volunteer novice teleoperators recruited from a population of graduate and undergraduate robotics students at Johns Hopkins University (JHU). Tests were approved by the JHU Homewood Institutional Review Board (HIRB00000701). Four right-handed participants completed the trials (3 male, 1 female).

A repeated measures experimental design was used in which all participants performed the cutting operation under each condition once. The order in which the test conditions were presented to operators was random and balanced. Users were given a chance to practice significantly under each control scheme before performing the tests.

The tests were performed as described in [3]. For each test, the cutter was positioned into a pre-cut slit in the tape seam and oriented parallel to the cutting plane. Users then cut a $140\,\text{mm}$ line along the seam of one section of mock MLI blanket, with start and end points indicated by white paint on the blanket. After each trial, users completed a computer-administered NASA TLX survey [27].

### D. Data Analysis

The states of the MTM and WAM robots were logged for all trials, as well as the measured and commanded Cartesian position of the cutter tip. These logs are used to determine the average cutting speed and cutting path error for each trial. Assuming an ideal path to be a straight line, the cutting path error is defined as the deviation from the linear fit to the overall cutter path in the cutting plane. The root mean square of the cutter path error provides a single metric to describe path error for a single trial. Note that both cutter speed and cutter path RMSE are normalized by overall path length to account for variations in cutter trajectory.

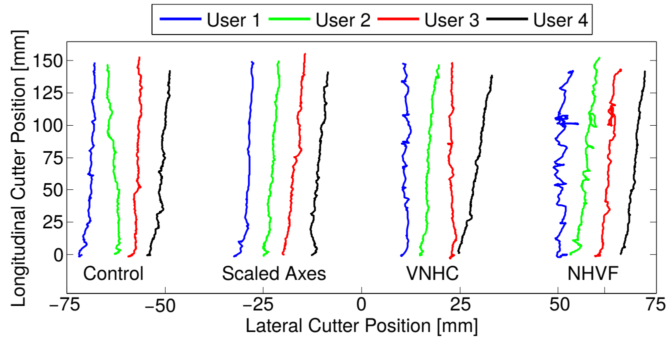


Fig. 5: Paths traced by the cutter in the cutting plane for each trial, grouped by condition type. Paths have been artificially spaced in the horizontal axis for legibility.

Following each set of tests, the cut sections of Kapton tape were carefully removed from the MLI blanket, mounted on paper, and digitally scanned for analysis of edge roughness via root-mean-square-error (RMSE) of the tape edge (as cut by the robot), as described in [3].

## V. RESULTS

This section reports the results of the pilot study.

### A. Path Error

Figure 5 shows the planar ($x$-$y$) path of the cutter for each trial, and provides a visual summary of the effect of the different teleoperation approaches on the motion of the teleoperated cutter. In the control test, small lateral deviations are observed throughout the cut as a result of the operators' inputs not being perfectly straight. As expected, the scaled axis reduced the impact of these unintentional deviations.

Imposing the VNHC allowed for long periods of relatively straight paths without lateral motion, and there are clear indications where the user stopped to turn the cutter. These segments of relatively straight piecewise cutting paths could potentially be preferable to the type of paths produced with the unconstrained controllers.

The NHVF tests show short segments of straight paths, but overall the paths are much less straight than the other conditions. It appears as if the operators were working against the virtual fixture by frequently readjusting the cutter steering angle. This was not necessary, as the NHVF would steer the cutter to an appropriate path, but several operators noted that they actively tried to change the cutter angle because they did not like the path presented to them. Using different gains for the NHVF controller and allowing the user to shift the virtual fixture laterally rather than just adjust the steering angle could make users more likely to accept the presented path, which could result in smoother cutting paths.

The observations above are reflected in the path error RMSE for each trial shown in Fig. 6. The overall path RMSE

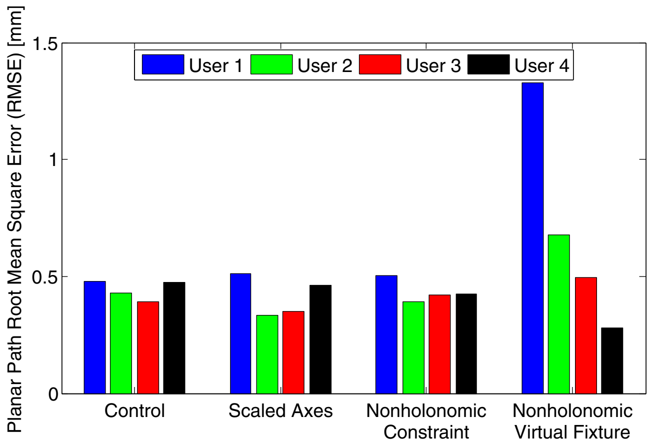


Fig. 6: RMSE of cutter path for each trial.

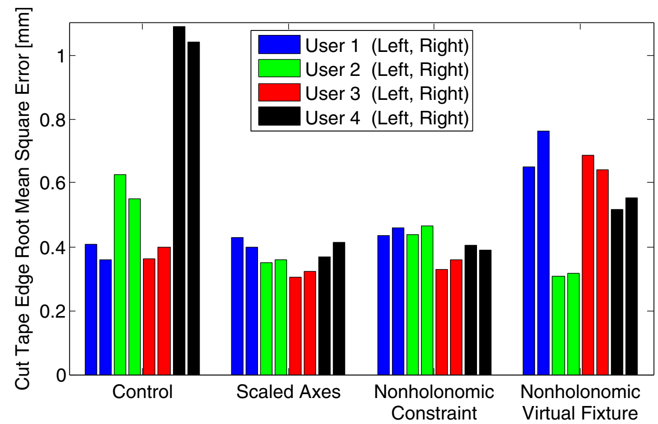


Fig. 8: RMSE of left and right cut tape edges for each trial.

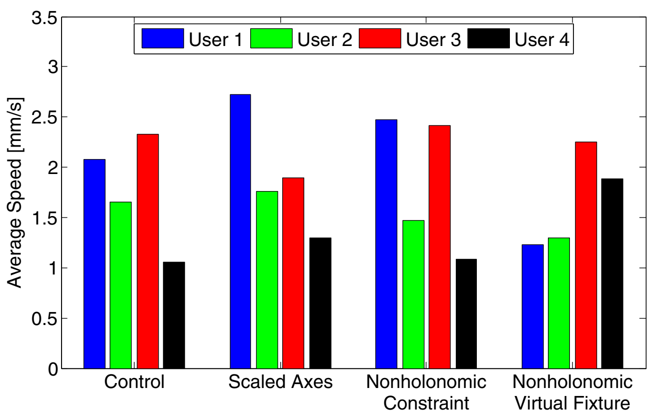


Fig. 7: Average cutting speed for each trial.

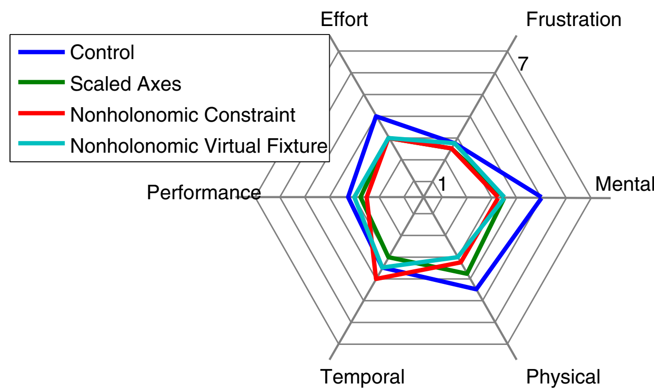


Fig. 9: Radar plot of average categorical workload from NASA TLX survey as self-reported by the operators. Higher workloads are farther from the center.

is similar for the control, scaled axes, and VNHC trials, and is generally higher for the NHVF runs. Also note that the lowest path RMSE was achieved with the NHVF control test, from a user who provided only minimal adjustments to the projected path during this run.

### B. Cutting Speed

The average cutter speed for each trial is shown in Fig. 7. The speeds of individual operators appear to be consistent across all test conditions, with little variation resulting from the type of constraint used. While the VNHC case did not result in faster cutting speeds, neither did it hinder the operators' ability to perform the task at their desired speed, despite the additional motion constraints imposed on the system. Thus, either the constraints had no effect on cutting speed, or the speed boost that might be expected from the reduced degrees of freedom of the system [28] was offset by the difficulty of controlling a nonholonomic system. The results of the operator workload survey, discussed in more detail in Section V-D indicate that it is likely the former.

### C. Tape Roughness

The roughness of the cut edges (left and right sides) of the tape as measured by RMSE are shown in Fig. 8. Similar to the path error, the scaled-axis and VNHC condition resulted in smoothest overall cut tape edges. Despite the erratic cutter motion in many of the NHVF cases, the cut edges are not proportionally rougher in that case than the edges produced from the other controllers. Again, if operators were more comfortable with the path obtained with the NHVF controller, the cuts could have been smoother.

### D. Operator Workload

Figure 9 shows the mean ratings of each workload category reported by the operators in the NASA TLX survey. All test conditions resulted in less overall workload than the control test, though both tests with the VNHC imposed slightly higher temporal demand. Surprisingly, the NHVF case did not result in higher frustration than the other control approaches, despite operators frequently readjusting the path. A more intuitive implementation of the NHVF could potentially decrease frustration as well.

## VI. CONCLUSIONS

This paper introduces the concept of a virtual nonholonomic constraint (VNHC) that can be used to assist operators during teleoperated robotic tasks, especially under significant time delay. While nonholonomic constraints are often viewed as detrimental to teleoperation performance, carefully chosen constraints may reduce the number of user command inputs a teleoperator must command to the robot and, in consequence, reduce the potential for unintentional commands to be sent to the robot without decoupling the input degrees of freedom. We also introduce a new type of soft virtual fixture that is subject to a VNHC.

We describe the implementation of a VNHC and a nonholonomic virtual fixture (NHVF) for use in a time-delayed teleoperation task based on a satellite servicing mission and report the results of a pilot study to compare the performance of teleoperation with a VNHC and a NHVF to more traditional approaches for planar multi-layer insulation (MLI) tape cutting. The results indicate that teleoperation subject to a VNHC yields similar performance to a holonomic Cartesian control scheme, without loss of speed or cut quality. The cutting paths produced under the VNHC consist of a sequence of straight segments rather than the continuously varying line produced with the control tests. The implemented NHVF resulted in worse path error, and a slight reduction in cut quality, but no loss of cut speed. However, it appeared that the users in this trial would have preferred a different implementation of the NHVF with more adjustability. Finally, users reported less workload with the VNHC and NHVF than under the control case. Thus, it appears that despite the loss of an input degree of freedom, teleoperation subject to a VNHC did not compromise the users' ability to perform the cutting operation, and was less taxing than commanding all three planar degrees of freedom.

Limitations of this study include the small sample size of subjects tested and the use of novice teleoperators. The results are also limited to straight-line cutting scenarios without significant deviation under a constant 4 s delay. Nevertheless, the results show promise for the use of VNHCs in time-delayed teleoperation.

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