Discontinuity Detection for Analysis of Telerobot Trajectories

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Objective:

To identify spatial and temporal discontinuities in telerobot movement in order to describe the shift in operators' control and error correction strategies from continuous control to move-and-wait strategies. This shift was studied under conditions of simulated increasingly time-delayed teleoperation. The ultimate goal is to determine if the time delay associated with the shift is invariant with independently imposed control difficulty. We expect this shift to manifest itself as changes in the number of discontinuity of movement path.

Background

In general, there are two types of discontinuities:

· Spatial Discontinuities (SD): abrupt changes in operator and/or telerobot movement direction in three-dimensional space.

· Temporal Discontinuities (TD): intervals during which the operator/telerobot pause momentarily at a particular location.

We designed our study of misalignments between the human operator's local control frame and their rotated viewing frame by dissociating the human operator's local control frame from their simulated remote worksite to impose measured amounts of control difficulty to address our original objectives.

Introduction

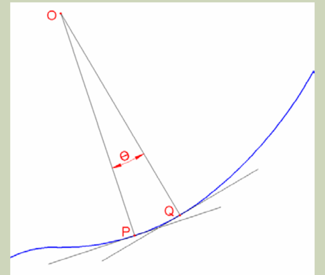
We began our analysis of discontinuities with an examination of the spatial properties of curvature in two-dimensions. We have now extended the analysis to the properties of in three-dimensional space. In addition, we have developed an adaptive temporal discontinuity detection algorithm that detects pauses in telerobot movement whenever both distance and speed fall below a pre-defined threshold over a given number of successive trajectory sample points.

Methods

• **Spatial Discontinuity** (SD) detection using the property of curvature

a. Inspiration from 2D curvature: Our previous analysis, which used the coefficient of the second order polynomial on projected 2D trajectory to examine discontinuity, showed that curvature might be fit to explain any abrupt change in teleoperation. Since curvature depends only on the shape of the curve, it should not be changed when the point of view of observer is changed.

b. The underlying idea is that the magnitude of curvature is a measure of how sharply a curve bends. Curves that bend slowly will have small absolute curvature. Alternatively, a curved region that exhibits a sharp turn will have large curvature.

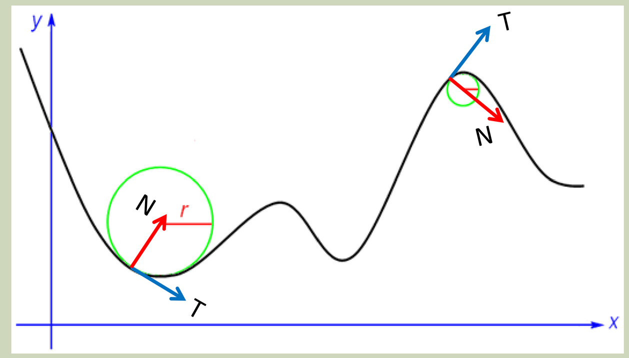


Radius of curvature

The curvature k is the rate of change of direction at that point of the tangent line with respect to arc length, that is,

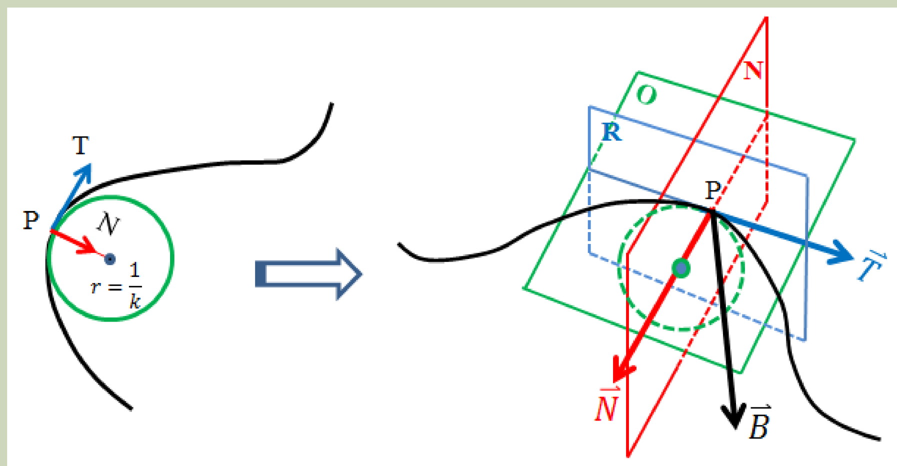
$$r = \lim_{Q \to P} \frac{\Delta \widetilde{PQ}}{\Delta\theta} = \frac{ds}{d\theta}, \quad k = \frac{1}{r} = \frac{d\theta}{ds}$$

First, we draw an osculating circle with its circumference tangent to the curve and its center, by definition on a line normal to the tangent point. The radius of this circle is the same as the curvature of the curve at the tangent point.



Variation of curvature along the curve

The OC is then resized as it is moved along the planar trajectory to detect abrupt change in curvature. We then extend 2-D osculating circle into 3-D osculating disc by introducing Frenet-Serret (Tangent-Normal-Binormal, or TNB) coordinates along the curve. If the curve *P*(*t*) is parameterized by time *t*, *the tangent to the curve is given by P'*(*t*) and points in the direction of motion along the curve.



Osculating disc on 3D space by TNB frame

$$\vec{T}(t) = \frac{\vec{P}'(t)}{\|\vec{P}'(t)\|}$$

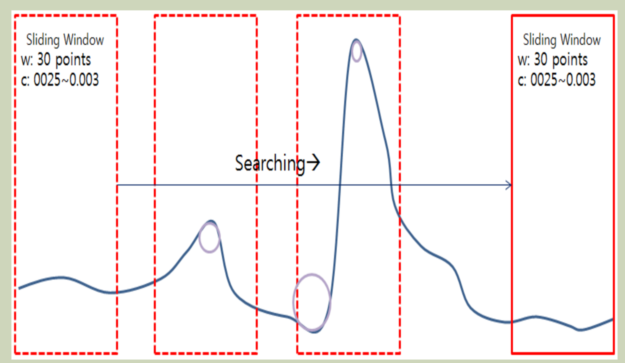
$$\vec{N}(t) = \frac{\vec{T}'(t)}{\|\vec{T}'(t)\|}$$

$$\vec{B}(t) = \vec{T}(t) \times \vec{N}(t)$$

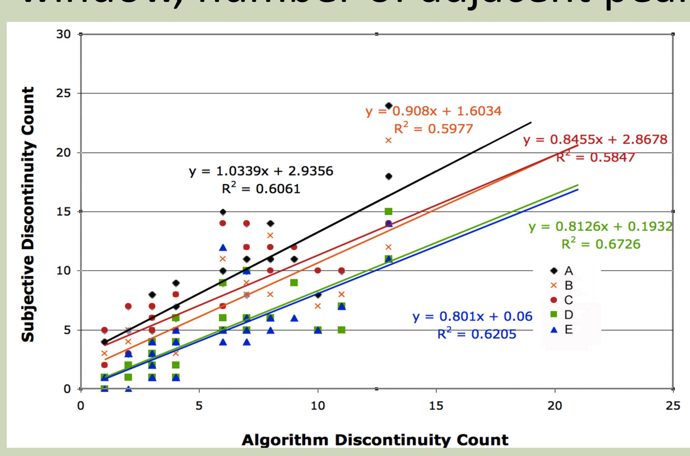
The curvature of a curve in three dimensions are defined via the following formulas. Namely, $\vec{T'}(t) = k\vec{N}(t)$, where k is the curvature of the curve at the point $P(t)$.

$$k = \frac{\|P' \times P''\|}{\|P'\|^3}$$

We next adjust three filter parameters (radius of curvature, length of search window, number of adjacent peaks).



Search window for detecting max and min



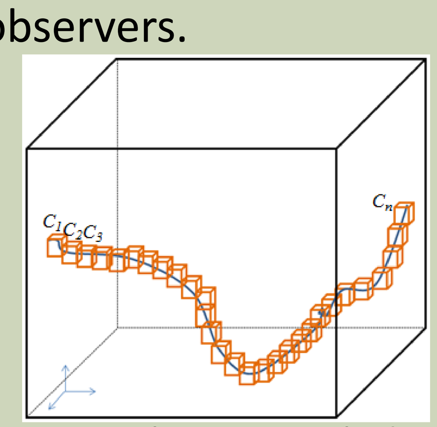
Validation of computational detection

The number of discontinuities detected by the automated algorithm was subsequently validated against the number of discontinuities identified by a panel of human observers.

· **Temporal Discontinuity** (TD) detection using a spatial distance between two adjacent sample points

a. We first calculate the length of two sample points.

$$Dist(C_i) = \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2}$$

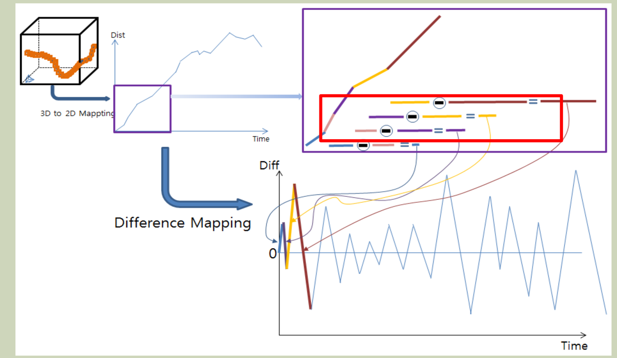


Segments by two sample data

We next convert distances/lengths into 2D coordinate systems in terms of time codes (Len). We then calculate the difference in successive distance(Adj, *red box*).

$$Len(i) = Dist(i) - Dist(i-1)$$

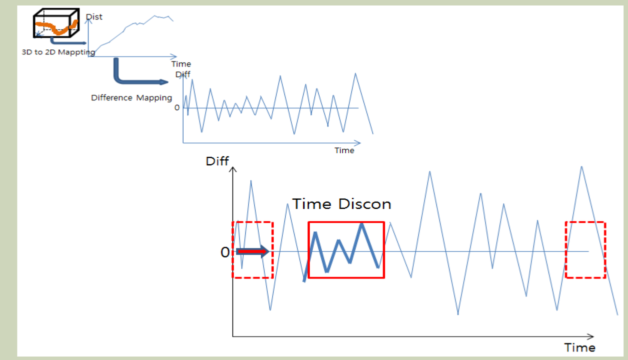
$$Adj(Len_{ti}) = Len(ti) - Len(ti-1)$$



Mapping diagonal length into the difference map of successive distance

Map the adjacent difference into 2D coordinate systems to see the changes in displacement between one time sample and the next.

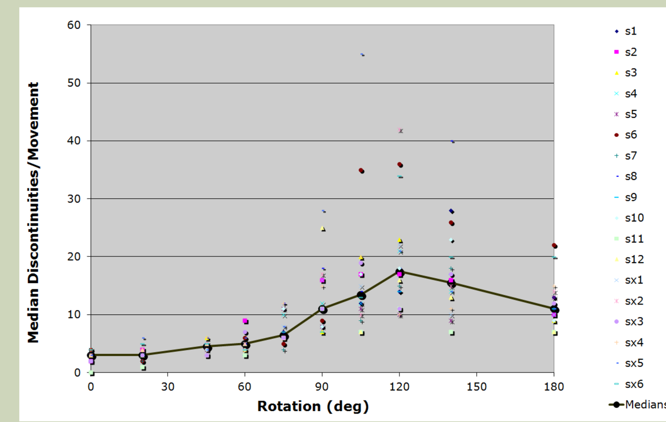
If search window meets any region whose the height is smaller than the given threshold, the region is considered as temporal discontinuity. In addition, If the height of next point after search window is still within the search window's the amplitude bound, that next point is also considered to be part (an extension) of the previously detected region



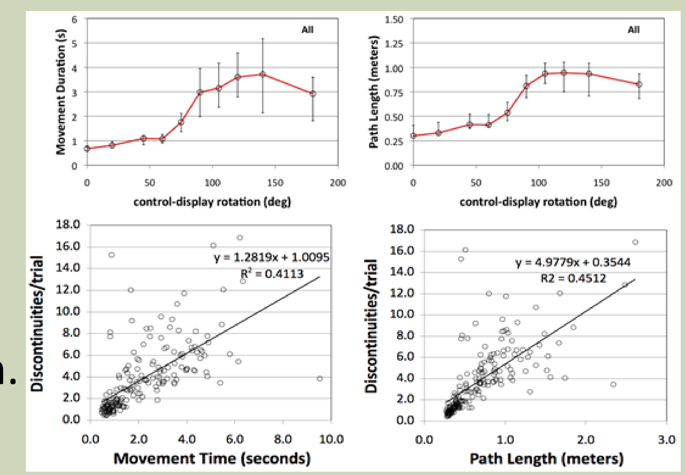
Search any region which has smaller height than the given threshold

Results

Trajectory data were collected from 18 participants, each of whom completed 210 trial movements. The result shows the average discontinuities count per movement trajectory (i.e., individual trial) across all target locations for each of the 18 participants as a function of control-to-display rotation angle. The discontinuity count per movement exhibits the pattern of skewed rightward with a peak between 105° to 120° of rotation. Correlation analyses of the 18 participants' responses at each of the ten control-display rotation levels indicate that the number discontinuities per trial is significantly correlated with both path length (r = 0.672, df = 178, p <0.001) and movement time (r = 0.641, df = 178, p <0.001).



Discontinuity count per movement



Correlation analysis of movement time and path length

Conclusions

We proposed an approach to spatial and temporal discontinuity detection algorithm for analysis of teleoperated trajectory in three dimensional space. The algorithm provides a simple and potentially objective method for detecting the discontinuity during telerobot operation and evaluating the difficulty of rotational coordinate condition in teleoperation.

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