Extraction of Precise Spatiotemporal Tactile-Motion Patterns in In-hand Manipulation using Sensing Glove

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***Abstract*—To investigate human manipulation, researchers have measured tactile inputs and motions of the human hand. Tactile measurement of a precision grip by recording tactile nerves have revealed detailed temporal relationship between tacile afferents and gripping force. Recently, sensing gloves enables us to measure manipulations with the whole hand. However, analyses of sensing gloves with higher spatial resolutions can improve the range of observation. In this paper using a sensing glove with high spatio-temopral resolutions and analyses to select tactile-motion variables focusing on precision, we extracted precise tactile points (PTPs) and precise motions (PMs) from a rotating cylinder manipulation. The PTPs are selected such that tactile points get active with high repeatability over trials and their active timings have low variance. Also, the PMs are selected such that motions appear with high repeatability over trials and their timings have low variance. As a result, we showed PTPs and PMs are localized both spatially in the hand and temporally in the task. Moreover, we compared patterns of PTPs and PMs extracted by two manipulations of cylinders with different centers of mass, which are with the identical regrasping procedures. We consequently suggest that patterns of PTPs and PMs characterize precise difference of manipulations that are not distinguishable by previous analyses.**

I. Introduction

How to control in-hand manipulation with a multi-fingered robotic hand remains a major theme in robotics. Althogh a controller for a in-hand manipulation is achieved analytically based on hybrid system theory, this cannot compute control input in real-time [11]. In contrast, the human hands can manipulate dexterously. To investigate how the human hands manipulate may contribute to a controller of a robotic hand.

Physiological studies have revealed tactile-motion control in precision grip. The human hands adjust fingertip forces to the local frictional condition detected by tactile mechanorecepters not to slip the manipulating objects [4]. Base on the experimental result, Gunji et al. developed a robotic hand with tactile sensors which can grip unknown various weighted objects [3]. However, physiological studies have technical and ethical difficulty in measuring a whole hand manipulation because they are based on invasive measurement.

Recently, development of sensing gloves and systems allows us to measure whole hand. Using a sensing glove with 15 tactile sensors, tactile patterns during grasp and place task are categorized to 7 pre-defined grasping templates [2]. Also, using 5 tactile groups, a transition of 32 pre-defined grasping patterns is categorized to 6 manipulation templates [5]. However, analyses characterizing manipulations using sensing glove with more tactile points can improve the range of observation.

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(a) Tactile sensor glove

(b) Motion capture system

Fig. 1 . Appearance of tactile sensing glove and hand motion capture system.

Researchers on human motion and robot control have focused on spatial and temporal variance of state-space. Uncontrolled manifold analysis can select coordinating variables in human motion based on spatial variance over trials [8]. Moreover, when humans and robots perform dynamic whole-body actions (role-and-rise task, for expamle), states-space with small variance sparsely located along the time axis is known to be a critical condition for a control to succeed [7]. However, the human hands have not been analyzed from the point of view of variance of state-space.

II. Materials and Methods

A. *Tactile-Motion Sensing Glove*

We employed tactile-motion sensing glove which has hand motion capture system and physiologically sound dense tactile sensing glove [9]. Hand motion capture system is implemented with inertia sensors on the back of the hand in order not to inhibit human manipulation (Fig. 1(b)). Hand motion capture system has 18 inertia sensors (222 fps). Tactile sensing glove has spatial and temporal resolutions comparative to be comparable to human hand (Fig. 1(a)). The spatial resolution is based on two-point discrimination of the human hand [10]. The glove has approximately 1000 pressure sensors, the number of which depends on size of subject's hand, at 1000 fps. This glove also minimize the inhibitation by being made thin.

B. *Precise Tactile Points and Motions*

We extracted PTPs and PMs by high repeatability and low time variance over trials (Fig. 2). The procedure to extract PTPs and PMs is as follows: (1) We segmented raw time-series to trials by tactile event, e.g., initial contact between a thumb and a manipulating object. (2) We linearly normalized

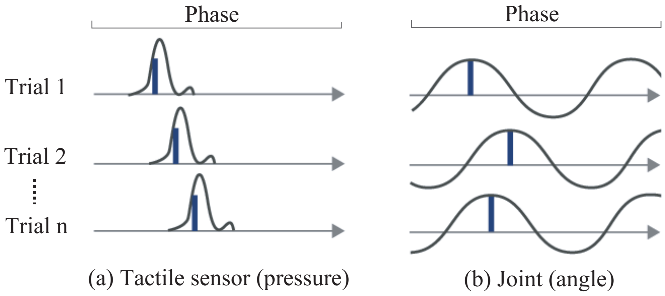


Fig. 2 . Precise tactile point (PTP) and precise motion (PM). (a) A tactile point that it gets active with high repeatablity and the variance of active timing is low. (b) A precise motor such that it extends or bends with high repeatability and the variance of motion timing is low.

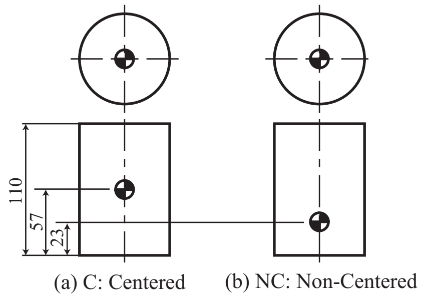


Fig. 3 . Manipulated cylinders.

Table I
SPECIFICATION OF THE CYLINDERS.

	Manipulation C	Manipulation NC
Weight	455 g	322 g
Height	110 mm	110 mm
Height of center of gravity	57 mm	23 mm
Diameter	72 mm	72 mm

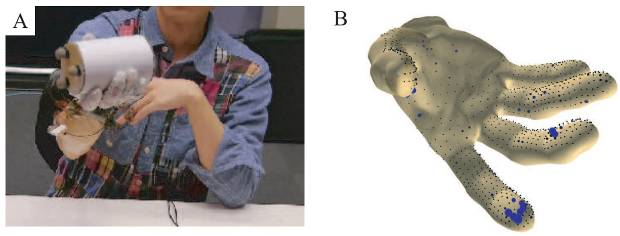


Fig. 4 . Overview of in-hand manipulation measurement. (A) Overview of experiment. (B) Reconstructed hand state using tactile sensing glove and motion capture system.

the length of time duration of trials to phase in $[0, 1]$. (3) We extracted tactile point activated for the first time and its timing for each manipulation segment. In the same way, we extracted motions defined as extention and bending for the first time and its timing for each segment. If a motion has 2 or more extention and bendings, we dismissed the motion. (4) If the tactile point which activates more than preset threshold (90%, here) of all trials and the standard deviation of the timing is less than preset threshold (0.15, here), we extracted them as PTPs. In the same way, if the motions which always extend or bend and the standard deviation of the timing is less than preset threshold (0.15, here), we extracted them as PMs.

To investigate spatial distribution of PTPs, we visualized PTPs by plotting on a 3D model of the hand, which was scanned by 3D scanner.

To examine temporal distribution of PTPs, we used *mean active rate* as the index to indicate the instantaneous number of active PTPs. Mean active rate is defined as the mean of the count of active PTPs in an interval of preset duration T (0.09, here). Tactile distribution of PTPs is calculated by the average over trials of mean active rate of PTPs for all phase. To investigate which PTPs are extracted in a specific time section, we visualized repeatability of PTPs activated in the section by plotting on a 3D model of the hand.

III. MANIPULATION EXPERIMENT

A. Experimental Setup

We conducted a single-subject experiment to measure and analyse in-hand manipulation, rotating in-hand manipulation. The subject performed 2 rotating manipulations of cylinder objects with center of mass coinciding with the geometrical center (manipulation C) and biased one (manipulation NC) wearing the sensing glove (Fig. 3, Table I). The subject was told to just rotate the object on the table in one direction without any instruction of rotating velocity and regrasping procedure. To record natural manipulations, the subject was not told which of the two (C/NC) he was holding. The subject repeatedly rotated the cylinder 17 times in manipulation C and 26 times in manipulation NC. This experiment is conducted under ethical approval and informed consent of the subject.

B. Identical Regrasping Procedure in In-hand Manipulation

We observed the identical regrasping procedure in both manipulation C and NC (Fig. 5). Observed regrasping procedure is as follows:

A. Put the index finger and the fingers from middle to little on the object
B. Put the index finger to the object immediatele after rotating the object
C. Release and stretch the fingers from miggle to little.
D. Regrasp the object with all fingers
E. Bend a thumb and put it to the object

C. Result

We characterized manipulation C and NC respectively focusing on the numbers, spatial distributions and temporal distributions of PTPs and PMs. First, the number of PTPs was 99 in manipulation C and 186 in manipulation NC. Similarly, the number of PMs was 2 in manipulation C and 12 in manipulation NC (Fig. 9B, Fig. 7). This shows that the in-hand manipulations were characterized not by all tactile points and motions but by partial ones, PTPs and PMs. Second, both PTPs from manipulation C and NC were localized in from a thumb to the ring finger and the palm near a thumb (Fig. 8). Moreover, The PMs from manipulation C were localized in

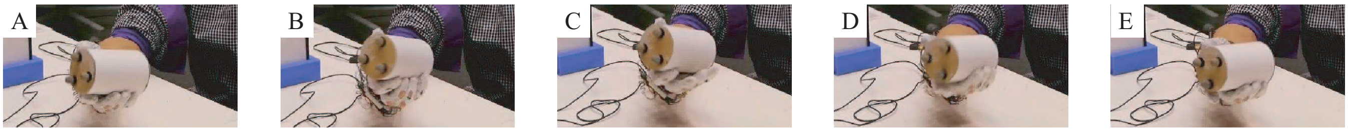
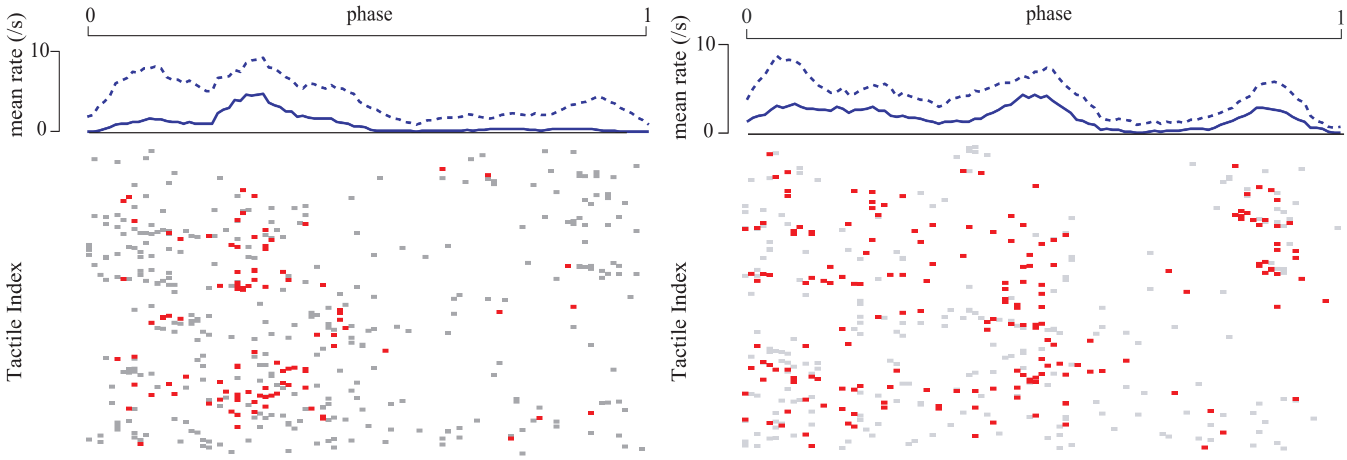


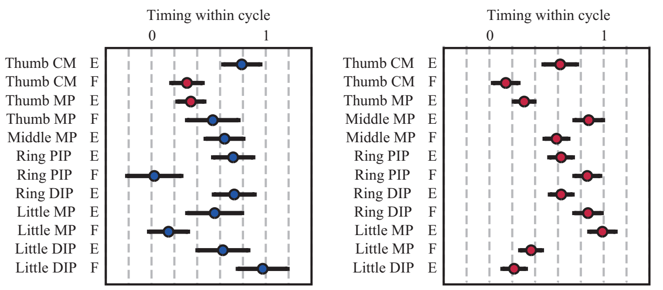
Fig. 5 . Snapshots of rotating manipulation. The pictures of A-E represent the corresponding regrasping procedure.



(a) Extracted tactile sensor and joint from manipulation C.

(b) Extracted tactile sensor and joint from manipulation NC.

Fig. 6 . Representative raster plots and mean active rate of PTP and non-PTPs from manipulation C and NC. Red points indicate PTPs. Gray points indicate non-PTPs. Blue solid line represents mean active rate of PTPs. Blue dashed line represents mean active rate of all tactile points.



(a) Extracted joint from manipulation C.

(b) Extracted joint from manipulation NC.

Fig. 7 . Temporal distribution of PMs from manipulations of C and NC.

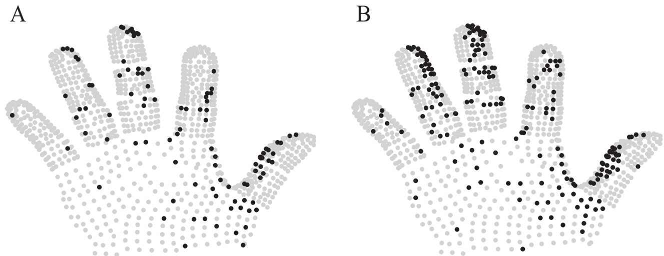


Fig. 8 . Spatial distribution of PTPs from manipulations C and NC. (A) Spatial distribution of manipulation C. (B) Spatial distribution of manipulation NC.

motions of a thumb. The PMs from manipulation NC were also localized in motions of the fingers except for second finger (Fig. 7). We found spatial distributions of PTPs and PMs was localized. Third, temporal distrivution of PTPs and PMs was also localized. The representative segment shows that the PTPs from manipulation NC are localized in 3 time sections and the PTPs from manipulation C are localized in 2 time sections. Also, the PMs from manipulation C and NC were localized along the time-axis (Fig. 7). We therefore found temporal distribution of PTPs and PMs were localized.

To examine the difference of PTPs and PMs between manipulation C and NC, we compared manipulation C and NC focusing on share of spatial distributions and temporal distributions. First, the PTPs extracted from manipulation C shared 70% (69 points) of these from manipulation NC (Fig. 9B). The number of the PTPs only from NC was 117 points (11.5% of the total). Also, all the PMs from manipulation C were extracted from manipulation NC. This suggest that there are common and task-specific PTPs and PMs. Second, we found there was three sections defined by local minima of the all tactile points. In the third section, the PTPs was found only from manipulation NC (see blue sections in Fig. 10AB). The temporal difference of PTPs were localized in a specific section. Third, visualizing the spatial distribution of the PTPs in each section, we found two spatial differences: on the one hand, PTPs in the third finger and fourth finger was different in the third section (Fig. 10EH). On the other hand, PTPs in the pulp of the second finger differed in the second section (Fig. 10DG). We found spatio-temporally localized specific differences of PTPs and PMs.

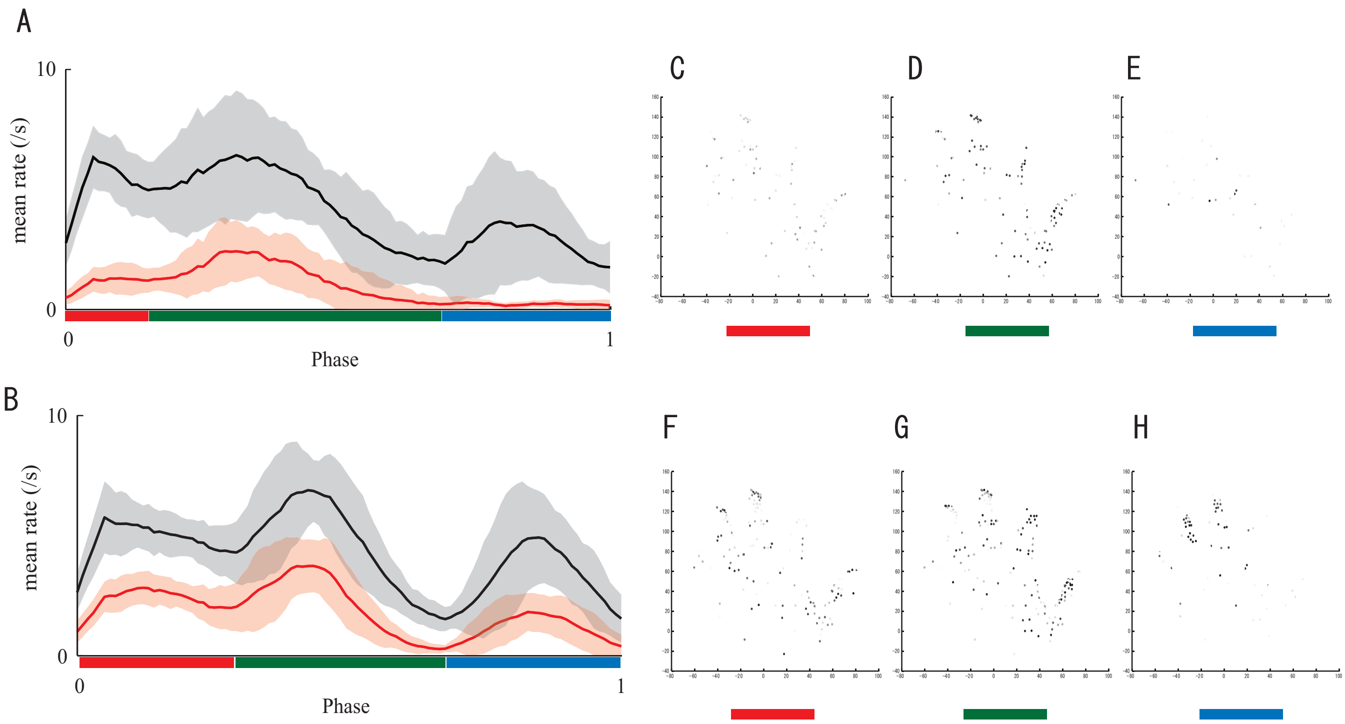


Fig. 10 . Spatio-temporal distribution of PTPs at each section. (A and B) The average over trials of the mean active rate of the tactile points in manipulation C and NC. Red solid line and envelop indicate the average and variance of the mean active rate of PTPs over trials. Black solid line and envelop indicate the average and variance of the mean active rate of all tactile points over trials. (C-E) Spatial distribution of PTPs extracted from manipulation C at each section. (F-H) Spatial distribution of PTPs extracted from manipulation NC at each section.

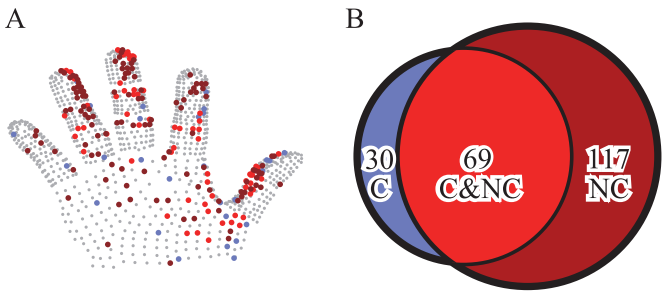


Fig. 9 . Share relationship between PTPs in manipulation C and manipulation NC. (A) Spatial distribution of PTPs in manipulation C and NC. Light red points represent PTPs in manipulations both C and NC, blue points from only from manipulation C, dark red from only from manipulation NC. (B) A Venn diagram of PTPs from manipulations C and NC.

IV. Conclusion and Discussion

In this paper using a sensing glove with high spatio-temopral resolutions and analyses to select tactile-motion variables focusing on precision, we extracted precise tactile points (PTPs) and precise motions (PMs) from a rotating cylinder manipulation. The PTPs are selected such that tactile points get active with high repeatability over trials and their active timings have low variance. Also, the PMs are selected such that motions appear with high repeatability over trials and their timings have low variance. As a result, we showed PTPs and PMs are localized both spatially in the hand and temporally in the task. Moreover, we compared patterns of PTPs and PMs extracted by two manipulations of cylinders with different centers of mass, which are with the identical regrasping procedures. We consequently suggest that patterns of PTPs and PMs characterize precise difference of manipulations that are not distinguishable by previous analyses.

Although control for dextrous manipulation with robot hand is an important open problem [1], there have not been a realistic controller. On the other hand, dynamic whole-body actions including complex contacts with the ground, for example roll-and-rise task, are known to have a ”knack”, an extremely narrow region in state-space to success [7]. The knacks is extracted by measuring human roll-and-rise task based on convergence of the variance of motion trajectories. Focusing on the knacks extracted from human measurement, a real adult-size humanoid robot performs roll-and-rise motion [6]. Similar to dynamic whole-body actions, we consider that PTPs and PMs extracted from human in-hand manipulation enables control of robotic in-hand manipulation.

We show that the human hands adapt to a more difficult manipulation by adding PTPs patterns. Manipulation NC is more difficult than manipulation C because the center of gravity of the cylinder used in manipulation NC is closer to the edge of supprting hand polygon than manipulation C. Focusing on the difference of PTPs patterns, additional spatio-temporal patterns are extracted only from manipulation NC. This implies that more difficlt task requires more additional TPT patterns to stabilize the manipulation.

In future work, we will conduct experiment to extract precise tactile-motion patterns from other in-hand manipulations. On the longer term, we plan to construct a robot controller using precise tactile-motor pattern extracted from human in-hand manipulation.

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