Using Haptics To Probe Human Contact Control Strategies For Six Degree-of-Freedom Tasks

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ABSTRACT

Transferring human contact-manipulation skills to robots is complicated by the combinatorial growth in contact state descriptions with object and environment complexity, with no systematic method to characterize the subset of contact states that humans actually control. In this paper, we present an approach to determine whether human subjects control specific contact states. Subjects used a six degree-of-freedom haptic interface to place a box on a plane, and insert L- and S-shaped objects into corresponding holes, while using either their (undetermined) natural strategies or explicitly controlling a pre-specified sequence of contact states. We found that the vast majority of contact states were visited for time periods of less than 40ms, which negates the possibility of human feedback control due to physiological delay limits. Next, using force, moment and velocity trajectories around contact state transitions as a metric, we found that certain states were readily discriminable across natural and explicit control strategies (∼ 85%), which indicates that they were not controlled during natural motions. Less discriminable states, in contrast, were likely to have been controlled in both natural and explicit strategies. Our results suggest that humans explicitly control a small subset of contact states, and that their control strategies are reflected in local force and velocity profiles. We thus demonstrate that six degree-of-freedom haptic simulations are effective for characterizing human contact-state invariant control strategies.

Keywords: Perception and psychophysics, haptic; Force rendering; Virtual environment modeling; Manufacturing/assembly

1 INTRODUCTION

A fundamental problem facing human-robot transfer learning is to characterize human contact-control strategies for creating control primitives and adapting haptic interfaces and force rendering algorithms for human-robot teaching by demonstration. Unlike free-space rigid-body motions, which are readily described by spatial trajectories controlled with potential fields [5] or proxies [12], motions in contact also require describing contact dependent kinematic and force constraints [11, 14]. One approach describes contact states as kinematic configurations where one or more vertices, edges, or planes of an object contacts another, and organizes the states and transitions between them into a graph. While contact control trajectories are readily described by graph traversals [4], the graph size grows combinatorially with contact states [6] and accumulated errors across graph traversals can cause deadlock. Humans, in contrast, efficiently perform tasks with many contact states. Characterizing human control strategies thus devolves into factorizing contact graph traversals into continuously controllable sub-sequences that start and end at explicitly controlled contact states.

Research in transferring human contact-control strategies to robots has involved identifying complete sequences of intermediate contact states that connect arbitrary states in the contact graph, and engineering hybrid force-position controllers to transition between them [8, 7]. Such strategies successfully achieved contact

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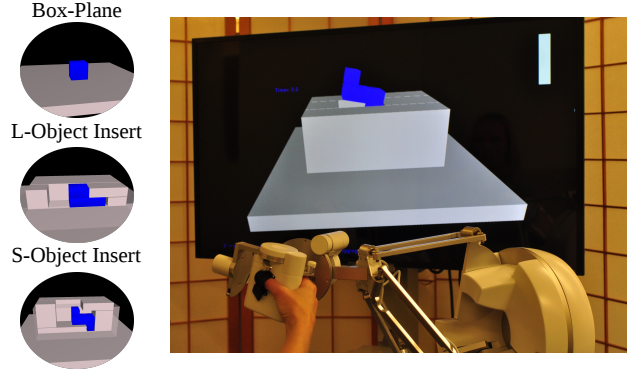*ellenrk7, †smenon, ‡keegango – @stanford.edu, §ok@cs.stanford.edu

Figure 1: Experimental conditions. Subjects manipulated three rigid objects, a box, an L-object and an S-object, using the Sigma-7 haptic device. Subjects placed the box on a plane, and inserted the L- and S-objects into corresponding holes. Each motion consisted of a free-space *'Hold'*, a *'Move'* to the goal, and a final *'Maintain'* at the goal.

control for tasks with few contact states, for instance, placing a box in a corner. This approach, however, does not readily accommodate learning from human demonstration because physical noise complicates identifying contact states in real world demonstrations, and humans rarely traverse the same contact graph trajectory even in noiseless virtual worlds. Moreover, even if humans repeatably seem to traverse the same trajectory, no method exists to characterize what states they explicitly control.

This paper outlines a novel approach to characterize human contact control strategies for complex contact manipulation tasks ($> 10^3$ nodes in graph). First, we present a six degree-of-freedom virtual haptic environment to deterministically identify the full sequence of contact states along human manipulation trajectories (Fig. 1). Second, we show that while humans visit a large number of contact states (5,064 for S-object; see Fig 2), they reliably only visit 2% of the states, and rarely visit even this subset for an amount of time that could indicate explicit control. Third, we use differences in contact state discriminability across natural motions and explicit state-controlling motions as a metric to determine whether contact states are actively controlled by humans as part of their natural manipulation strategies. Finally, we demonstrate that contact force and velocity profiles for subject populations match individual subjects, indicating the existence of a set of control strategies that can generally model human contact control.

2 DELINEATING CONTROLLED CONTACT STATES

To achieve our goal of delineating controlled contact states from uncontrolled ones, we designed experimental task conditions of increasing complexity. Our first task, placing a box on a plane, was succinctly described by a compliant contact controller [1] with only the goal state controlled, which matches the human uniform distribution across contact states (Fig. 2.B). Our next task, L-object insertion, introduced a non-uniform contact state distribution and dramatically increased complexity (9 to 5213 visited contact states) to a degree where subjects could not possibly control all states, which provided an avenue to contrast controlled and uncontrolled contact states. L-object insertion, however, is heavily constrained once the
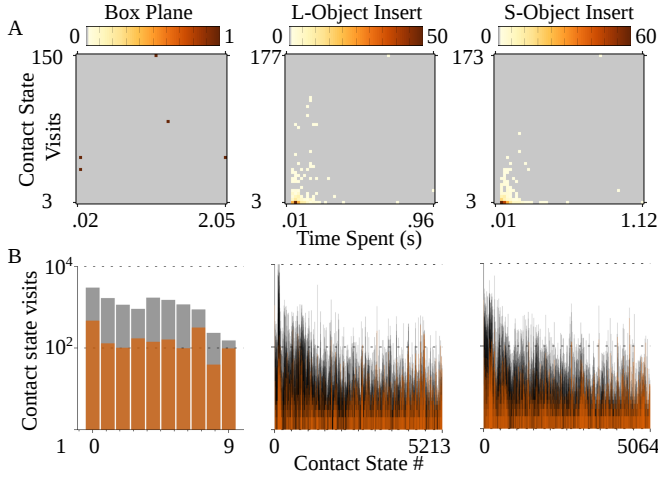
Figure 2: Most Contact States are Rarely Visited. *A*, A heat map shows the number of contact states as a function of the number of contact state visits and average time spent per visit. Data for eleven subjects; colorbar shows the number of unique contact states. *B*, A histogram of the contact state visits demonstrates that most contact states are rarely visited during L- and S-object insertion (<10 times); note the dramatic increase in contact states and graph complexity with respect to box-on-plane.

object is in the hole, which limits the space of potential control strategies. Finally, our S-object insertion task provides enough freedom within the hole for a variety of human contact control strategies. Our tasks demonstrate combinatorial growth in contact states and allow us to test whether force and velocity transients convey enough information to delineate controlled contact states.

2.1 Selecting Reliable Contact States to Analyze

Humans visit a large number of contact states as task complexity increases, but reliably visit only a small subset of these states. For our analysis, we collected preliminary data and identified these commonly visited states by eliminating states that subjects visited for less than 50ms on average (Fig. 2.A). From these, we selected edge-plane and plane-plane contact states, B1–B3, L1–L3, S1–S4 (Fig. 3), to test whether they were explicitly controlled or not.

2.2 Characterizing Explicitly Controlled States

We characterized explicitly controlled states by measuring forces and velocities from subjects as they transitioned through the state during natural motions, or when asked to explicitly control the state. Next, we used an $\mathscr{L}_1$-regularized logistic regression classifier [13] with leave-40-out cross validation to discriminate explicitly controlled contact state trajectories ($\pm$ 50ms temporal window around state transition) from natural motions. Box-on-plane motions were readily discriminable (median; 95% C.I: B1, .866;.844,.886. B2, .915;.897,.932. B3, .888;.867,.909), which, given the limited contact states, indicates that controlling even a single state explicitly influences the entire trajectory and suggests that the task is too simple for analyzing human contact strategies on a state-by-state basis (Fig. 3.A). Unlike box-on-plane's overlapping classification accuracy, L-object insertion exhibited significantly lower accuracy for the L2 and L3 states, which indicates similar subject trajectories for explicitly controlled and natural motions—we predict that a generic human strategy is to explicitly control both. Similarly we predict that S-object insertion's S4 state is explicitly controlled.

2.3 Individual Subject and Group Strategies Match

Analyzing our data for individual subjects, we found that box-on-plane classification was consistent with the group average but L- and S-object insertion exhibited greater variability for contact states inside the hole. This expected decrease in consistency resulted in
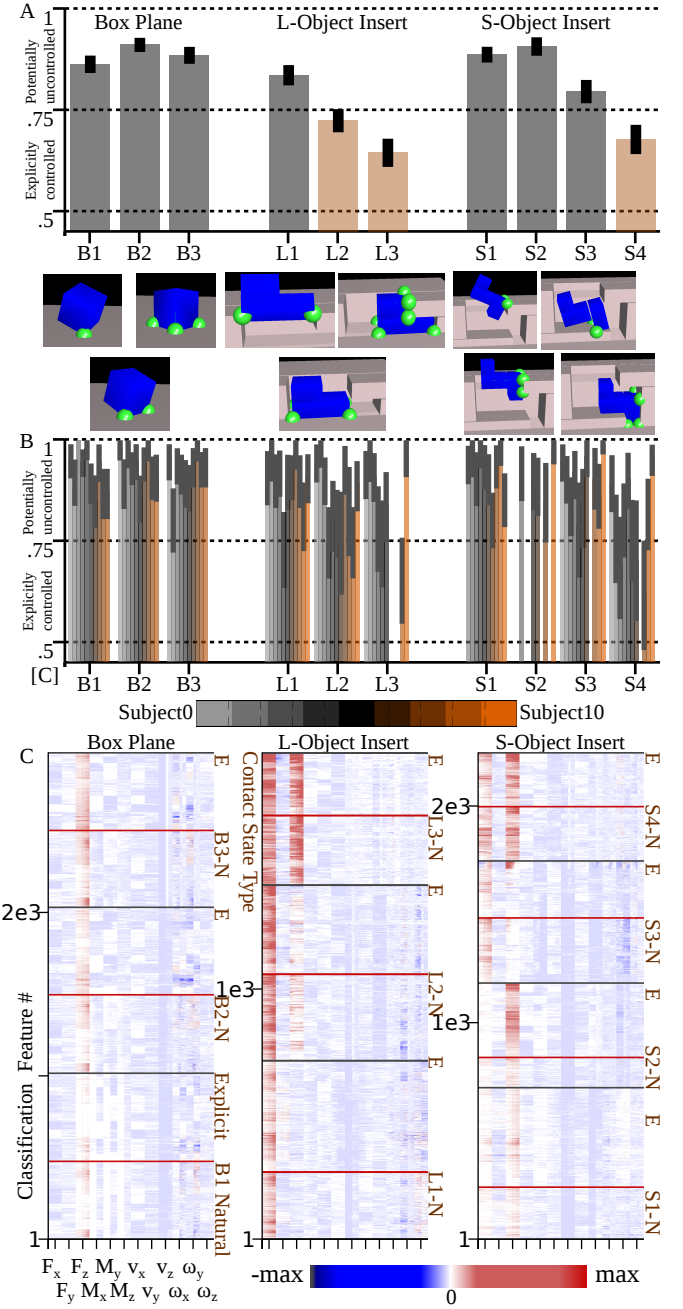

Figure 3: Identifying Explicitly Controlled States. We tested contact state discriminability across natural motions and motions with explicitly controlled states for subjects as a group (*A*) or individually (*B*) (Bootstrap median classifier accuracy; 95%C.I.). Less discriminable states implied explicit control (brown), while more discriminable states implied large differences between conditions (gray). Features were direct force (F), moment (M) and velocity (v, ω) measurements (*C*) to match robot sensor input. Order: trial type (col), contact state (row); natural and explicitly controlled motions separated by a red line.

some subjects failing to visit explicitly controlled states during natural motions (<15 times; bars removed), and in non-uniform feature distributions for states (Fig. 3.C).

3 HAPTIC RENDERING FOR RIGID BODY CONTACT

Our haptic simulation environment uses a *Force Dimension Sigma 7* haptic interface, a dynamic proxy controller, and the *Open Dynam-*
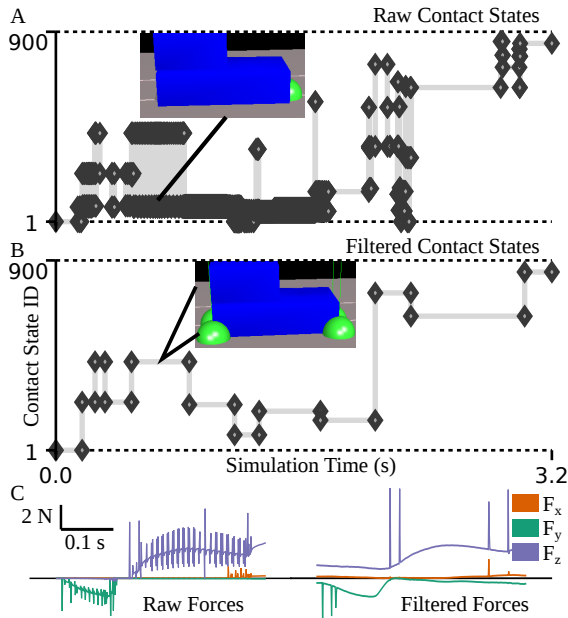
Figure 4: Haptic Contact Rendering. Physics simulation solvers can destabilize during contact motions and oscillate between contact states (*A*). For realistic haptic rendering, we implemented contact state estimation to eliminate oscillations (*B*), low-pass filtered noise, and re-added high frequency transients at contact transitions (*C*).

ics Engine for physics [3]. While dynamic proxies provide physically realistic dynamic collision forces, their second order control system introduces high-frequency resonances [9], which can destabilize the interface. The alternative, non-dynamic proxies [15, 12], make it hard to model collision transients and thus were not used. Since creating stable and physically accurate six DOF haptic simulations is an area of active research [2, 10] in general, we decided to customize the dynamics engine for our particular tasks. To do so, we mapped device positions and orientations to a control frame, and applied PD control forces to move virtual objects towards the frame (updated at ~1KHz). We mitigated high frequency resonances by applying haptic feedback using an undamped spring with high-frequency contact-dependent force transients and gain scaling (Fig. 4) to mimic stiff contact and allow subjects to easily detect contact transitions. In the process, we also filtered noisy physics engine contact states to estimate the actual contact state. We did so by tracking active contact vertices and allowing them to remain active for sixteen integration time-steps after the activating contact point disappears, which helps recognize stable contact states whose contact vertices appear in alternating groups. This approach, however, is presently limited to composite cuboid objects.

4 DISCUSSION

To summarize, we present a novel method to characterize the subset of contact states that humans explicitly control during rigid body manipulation tasks. We determined that while humans visit many states (>5,000 for L-object), they reliably visit only a small subset of the states (~2%), which indicates that their control strategy is invariant to most contact states. We also demonstrated that force and velocity trajectories near contact state transitions convey enough information to predict whether contact states are explicitly controlled. Our results promise to enable the systematic characterization of human contact control strategies for complex tasks, with applications to robotics, telemanipulation, and understanding human control.

APPENDIX. Haptic Protocol: Haptic experiments were conducted at Stanford University's Artificial Intelligence lab, with a right-handed Sigma 7 haptic interface. Subjects were pre-trained over 20 trials to apply control forces and moments within the de-

vice's limits, which were indicated with a slider bar on the screen (removed later for data-trials). The time taken was displayed and the longest time taken from the last ten training trials was set as the upper bound. Subjects then performed data trials with randomized environment configurations. A success or failure message was displayed in text if the peak force or maximum time was exceeded. First, subjects performed data trials using an unspecified natural strategy. Next, a sequence of contact states was specified for explicit control, with a failure message if any contact state was missed. (50 trials for each task, and for each natural/explicit condition). **Human Subjects:** Healthy, right-handed subjects with no history of motor disorders: 20m:6'0", 28m:5'9", 31f:5'4", 20m:6'0", 19m:6'0", 20m:5'7", 29m:5'11", 21f:5'2", 32m:5'11", 30m:5'8", 29m:5'8". Informed consent obtained in advance on a protocol approved by Stanford University's Institutional Review Board (IRB).

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