Non-prehensile transport can potentially streamline many robot tasks as it handles objects easily, transports multiple objects simultaneously, avoids computation for rigid grasps, and requires minimal end-effector actuaion. However, non-prehensile transport requires balancing inertial and frictional forces to prevent objects from falling and reduce sliding. While slower motions often ensure safety, they compromise the speed advantage of robots. This challenge motivates us to explore faster motions while carefully managing forces on the transported objects to avoid damaging them.

We propose a modular work cell setup where a robotic manipulator uses a tray to transport objects, adaptable to a wide range of manufacturing scenarios that require fast object handling. A key safety concern, especially when moving large or fragile objects, is minimizing any movement of the object relative to the tray. While recent works have addressed the challenges of fast non-prehensile transport by incorporating friction-based constraints to secure objects, they do not specifically aim to minimize object displacement, which occurs when the Coulomb friction model fails to account for some real-world factors during fast transport. As prior work, GOMP-FIT, provides a motion planning framework that ensures smooth and time-optimized trajectories under specified constraints, this work focuses on constraint design. Specifically, we investigate the dynamic interactions between the transported objects and the tray to develop a motion-based constraint that minimizes displacement and optimizes speed at the same time.

We start with a baseline Coulomb friction constraint. It regulates the ratio between a transported object's tangential and normal inertial accelerations relative to the tray surface, using a constant friction coefficient measured experimentally. While the baseline constraint effectively prevents object from falling, we propose FAST: friction-aware non-sliding transport with learned motion-based non-prehensile constraints, to further reduce object displacement. FAST formulates a motion-based constraint to account for factors not characterized by the friction coefficient. For instance, we observe intensified tray vibrations at higher velocities, which intermittently break contact, violating the assumptions of static Coulomb friction.

Vibro-tactile sensing offers advantages including low cost, high sampling frequency, minimal latency, ease of implementation, and resistance to environmental noise. Therefore, we attach a contact microphone to the tray to learn the motion-based constraint. The microphone detects vibrations caused by object sliding, which allows us to determine what motions lead to sliding with high precision. We then train a neural network to model a parameter that characterize these motions.

In experiments, we learn the motion-based constraints with data collected from a UR5e robot and 2 objects. We test the baseline constraint and the motion-based constraints on 8 objects with 12 different configurations. Experimental results suggest that the motion-based constraints can reduce the object displacement by up to 86.0 % compared to the baseline Coulomb friction constraint.