Robotic Nonprehensile Object Transportation with a Hanging Tray

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***Abstract*— We consider the nonprehensile object transportation task known as the *waiter's problem*, in which a robot must move an object balanced on a tray from one location to another. In contrast to prior work on the robot waiter's problem, which uses a tray rigidly held by the robot's end effector (EE), we use a tray *suspended* from the EE by ropes, such that it behaves like a three-dimensional pendulum. Some prior works have actuated the robot so that the EE *simulates* the behavior of a pendulum, because pendular motion reduces the shear forces acting on the transported objects, minimizing the sliding of rigid objects and sloshing in containers of liquid. In contrast, our use of a *real* hanging tray allows us to obtain the benefits of pendular motion while only actuating a 3 degree-of-freedom (DOF) mobile base, rather than requiring a full 6-DOF manipulator arm. Our experiments in simulation and on real hardware show that the hanging tray substantially reduces both sliding and sloshing compared to a static, rigidly-grasped tray.**

I. Introduction

The *waiter's problem* [1] is a nonprehensile manipulation task that requires a robot to transport objects balanced on a tray, like a restaurant waiter. Nonprehensile manipulation [2] occurs when the manipulated objects are not rigidly grasped, so they retain independent degrees of freedom (DOFs). In the waiter's problem, the objects are only attached to the tray by frictional contact, and thus they can slide or tip unless the motion of the robot is designed to avoid it. The use of a tray avoids the need to grasp and ungrasp each object, allows many objects to be transported at once, and can handle delicate objects which may be difficult to grasp at all.

Previous approaches to the waiter's problem (e.g., [3], [4]) use a tray rigidly attached to the robot's end effector EE and design complex controllers to rotate it in such a way that object sliding is minimized. A particularly interesting approach is to *simulate* the motion of a pendulum with the robot's EE, which naturally minimizes the shear forces acting on the transported objects without explicitly modelling them [5]–[7]. Inspired by these latter approaches, we take them a step further and use a *real*, physical pendulum rather than simulating the motion of one using control algorithms. That is, we *suspend* the tray from the EE so that it can swing freely like a three-dimensional (3D) pendulum, which means we do not need an actuated arm to rotate the tray nor do we need models of the transported objects. Indeed, in our experiments on the robot shown in Fig. 1, we only control the mobile base and do not move the manipulator arm at all. Our proposed approach is similar to the commercial SpillNot product [8], which is a suspended tray designed for carrying cups of liquid without spilling them. However, we are the first to use a suspended tray for nonprehensile object transportation on a *robot*. In addition, we integrate the hanging tray into an interactive robot waiter demonstration that uses an RGB-D camera to detect and serve people like a waiter.

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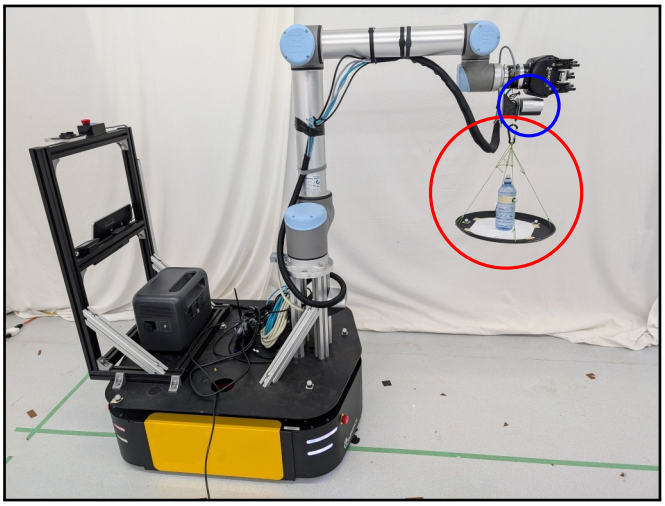

Fig. 1: We present the first work on robotic nonprehensile object transportation that uses a hanging tray (circled red) to support the transported objects. A key benefit is that an actuated manipulator arm is not necessary: in all of our experiments, we keep the arm stationary and only actuate the mobile base, allowing the swinging of the tray to naturally prevent the objects from sliding. An RGB-D camera (circled blue) allows the robot to detect human gestures and steer toward people to serve them. A video of the experiments can be found at `http://tiny.cc/visual-servor`.

II. Results

We validate our proposed approach with experiments on the real mobile manipulator shown in Fig. 1, which consists of a 3-DOF Ridgeback omnidirectional mobile base and a 6-DOF UR10 manipulator. However, since one of the key motivations for using a hanging tray is that the EE does not need to be actuated to prevent objects from sliding, we do not move the UR10 arm at all in any experiments; all motion is achieved with the mobile base alone, which is localized using a Vicon motion capture system.

A. Pendular Transport

Let us compare the behavior of the hanging tray and static tray in the real world. The static tray is held rigidly by the robot's gripper and the hanging tray is suspended from the EE using ropes, as shown in Fig. 3.

1) Rigid Objects: We begin with experiments transporting two different rigid objects: a short cup and a taller water bottle, also shown in Fig. 3. We command the base to move

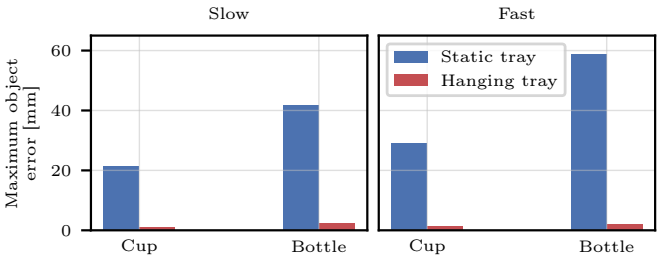

Fig. 2: Maximum object error across different combinations of trajectory profile, object, and tray type. The error is the maximum distance that the object moved from its initial position relative to the tray; each value is the average across three trials, with 24 experiments in total. The hanging tray results in substantially lower error than the static tray, because its swinging naturally reduces the shear forces acting on the objects.

Fig. 3: *From left:* The static tray, the hanging tray, and the two objects used in experiments: a water bottle and a cup.

in one direction with a particular motion profile and measure the distance the object moves from its initial position on the tray using motion capture. Two trapezoidal motion profiles are used: *slow* and *fast*. Starting from rest, the *slow* trajectory has a constant acceleration of $0.5\,\mathrm{m/s^2}$ for $2\,\mathrm{s}$, reaching a maximum velocity of $1\,\mathrm{m/s}$, before immediately accelerating at $-0.5\,\mathrm{m/s^2}$ for a further $2\,\mathrm{s}$ and returning to rest at $t = 4\,\mathrm{s}$. The *fast* trajectory accelerates from rest at $1\,\mathrm{m/s^2}$ for $1\,\mathrm{s}$ to reach the same maximum velocity of $1\,\mathrm{m/s}$. It holds this velocity constant for $2\,\mathrm{s}$ before accelerating at $-1\,\mathrm{m/s^2}$ for a further $1\,\mathrm{s}$ and returning to rest at $t = 4\,\mathrm{s}$.

For each combination of transported object (cup or bottle), tray (static or hanging), and motion profile (slow or fast), we perform three runs, for a total of 24 experiments. The maximum object error across of any of the three runs for each combination is plotted in Fig. 2. The hanging tray resulted in almost no sliding of either object for both motion profiles, with at most $3\,\mathrm{mm}$ of error. In contrast, the static tray results in over $20\,\mathrm{mm}$ of error in every case. While the commanded accelerations should theoretically be low enough for to avoid sliding on the static tray, unmodelled effects and vibrations result in object motion that the hanging tray avoids.

2) Liquid Handling: Previous work [7] on pendular motion was focused on transporting liquids while minimizing slosh and spillage, so we also perform an experiment to assess the hanging tray's ability to transport liquid without spilling. To avoid uncontrolled spills, we use a cup rigidly set within a larger container that is in turn rigidly attached to the tray (see Fig. 4). For each experiment, the cup is filled with $200\,\mathrm{ml}$ of water colored with red food dye, which is free to slosh out of the cup (but any spill is captured inside the larger container). As shown in Fig. 4, the hanging tray results in no spill, while a considerable amount of liquid sloshed out of the cup with the static tray.

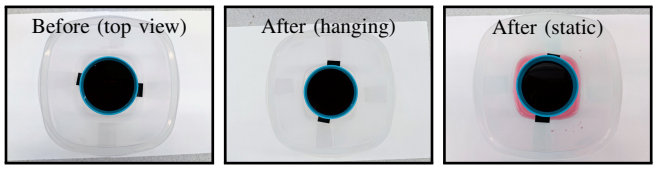

Fig. 4: Setup for the liquid handling experiments. The blue cup is rigidly set in the center of the larger plastic container and filled with $200\,\mathrm{ml}$ of water colored red with food dye. The water is free to slosh out of the cup but will be caught in the larger container. The container is rigidly attached to the tray during experiments. *From left:* Top view before experiments, after executing the fast trajectory with the hanging tray, and after executing it with the static tray. No liquid spilled from the cup when using the hanging tray, but a considerable amount was spilled with the static tray (the pink spill can be seen collected in the bottom of the larger container).

B. Interactive Robot Waiter

As a final experiment, we present a demonstration of our full interactive waiter using visual servoing. The robot is equipped with the hanging tray carrying four cups while two people are sitting nearby. An Orbbec Femto Bolt RGB-D camera attached to the EE is used to observe the scene. Each person raises their hand in turn to summon the robot and take a cup from the tray without leaving their seats. The full demonstration can be seen at: **`http://tiny.cc/visual-servor`**.

III. Conclusion

We presented an approach for robotic nonprehensile object transportation using a hanging tray, the dynamics of which naturally reduce the shear forces acting on the transported objects and prevent them from sliding. We demonstrated this approach using rigid objects, liquid, and in an interactive robot waiter experiment.

References

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