Robotic Edge-Rolling Manipulation: A Grasp Planning Approach

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Abstract—This paper presents a novel robotic manipulation technique that we call robotic edge-rolling. It refers to transporting a cylindrical object by rolling on its circular edge, as human workers might maneuver a gas cylinder on the ground. Our robotic edge-rolling is achieved by controlling the object to both roll on its bottom edge in contact with the ground and slide on the surface of the robot’s end-effector. It can thus be regarded as a form of robotic dexterous, in-hand manipulation with nonprehensile grasps. We address the problem of grasp planning for edge-rolling by studying how to design appropriately shaped end-effectors with zero internal mobility and how to find feasible grasps for stably rolling the object quasidynamically with our simple end-effectors. An extensive set of experiments is performed with a conventional manipulator arm on not only flat surfaces but also a U-shaped half-pipe track. Long-range edge-rolling is demonstrated with a modular mobile manipulator which is capable of active steering control.

Index Terms—Grasping; Grippers and Other End-Effectors; Dexterous Manipulation

I. INTRODUCTION

We introduce robotic edge-rolling, a novel robotic manipulation technique for moving cylindrical objects by rolling them on the circular edge of the bottom face. This method, with possible applications to object transportation, part reorientation, and the like, is an alternative to traditional grasp-lift-and-carry manipulation, which might not be possible when it comes to handling large, heavy objects beyond the carrying capacity of the robot. Fig. 1 depicts our robots edge-rolling the cylindrical object, along with human edge-rolling, as commonly performed with the gas tank.

As successfully demonstrated in [1], [2], cylindrical objects can be transported by rolling on their curved face. However, the potentially large footprints of the configuration can make it hard to navigate through a cluttered, unstructured environment. It may take a great deal of effort commensurate with the inertia of the object to steer the heading of the object rolling on its face. In contrast, edge-rolling requires very small footprints in the sense that the object stands on a point contact in principle.

This paper presents grasp planning for robotic edge-rolling manipulation with implementation on real robotic systems: an industrial robot arm and a modular mobile robot (Fig. 1(a-b)). Our technique is realized with very simple end-effectors with no internal mobility which can be fabricated as a single rigid body (Fig. 1(a-b)). It can be considered as a form of robotic in-hand manipulation in a nonprehensile manner since the object is controlled to slide on the surface of the zero-mobility end-effector while rolling on the ground surface and is, thus, closely related to the important issue of robotic dexterity. Utilizing our previous work [3], we also show that it is possible to acquire the resulting target grasps for edge-rolling in an autonomous manner.

It is also possible to edge-roll objects using multi-fingered, dexterous hands, as in human edge-rolling (Fig. 1(c)). For example, first the object may be firmly grasped by the multi-fingered gripper, and then the object-gripper system may be rotated together by means of the mobility of the rest of the robot. This prehensile approach has advantages including straightforward grasp planning. However, errors in controlling the object or the robot may result in large internal forces, which can get the system damaged and make edge-rolling impossible. We believe our approach using nonprehensile grasps with simple end-effectors can be more effective for negotiating large internal forces. Likewise, we believe that the approach will allow errors and uncertainties in perception and control to be handled in a more energy-efficient manner like many other underactuated, passive manipulation scenarios. In addition, our approach can be more practical in that our end-effectors use zero actuators.

After outlining relevant literature (Sec. II) and presenting
our problem statement (Sec. III), in Sec. IV we present our approach to effector design. In Sec. V we investigate how to find feasible grasps for stable edge-rolling. Sec. VI demonstrates edge-rolling with real robotic systems in some different environments.

II. RELATED WORK

The challenge task, edge-rolling, studied in the paper can be modeled as a quasidynamic manipulation process to address our target scenario in which a mobile robotic platform (for example, an industrial robot arm or a wheeled mobile base) manipulates the object with negligible momentum. According to [4], quasidynamic manipulation is intermediate between static and dynamic manipulation as if excessive damping prevents accelerations from integrating into significant velocities. Examples in the literature include the well-known peg-in-hole task, tray tilting for object reorientation [5], pushing primitives of a parallel-jaw gripper for regrasping [2], and, most recently, the planning of a stable pushing strategy for in-hand manipulation [6].

The main scope of work here is the problem of grasp planning for stable edge-rolling manipulation. Grasp planning concerns designing end-effectors and choosing grasps on objects of interest [4]. The problem has been addressed mainly in the context of robotic grasping and fixturing, which can be modeled as a quasistatic process. Previously, we addressed grasp planning for whole-arm grasping [7]. Important notions of the closure properties of robotic grasps include force-closure, form-closure, and immobilization [8]. In addition, partial closure properties (for example, partial force-form-closure) have also been investigated [9], [10]. The dynamic stability of a grasp depends on a variety of factors such as the geometry around contact, contact models, and material properties [11], [12]. Both model-based and data-driven algorithms for constructing stable robotic grasps are an active research area [13], [14].

Beyond grasping and fixturing, robotic pushing [15] is another practically important quasistatic manipulation technique. Other examples in the literature include object handling with flat contact surfaces [16], knocking an object over with a single contact [17], pivoting operation [18], push-grasping [19], and our previous work on stable picking and placing via two rigidly connected contacts [3]. Although dynamic manipulation is a relatively new area, some early examples can be seen in robotic juggling [20] and dynamic nonprehensile manipulation [21].

Also relevant to this work is robotic in-hand manipulation. It refers to the capability to reconfigure an object within a robotic hand. Various in-hand manipulation techniques have been realized in the forms of robotics regrasping, dexterous manipulation, and finger gaiting; see [22]–[26] and references therein.

III. PROBLEM DESCRIPTION

The problem we address in the paper is concerned with a novel robotic manipulation capability that we call robotic edge-rolling (recall Fig. 1). It refers to rolling a cylinder-shaped object on the circular edge of its bottom face. We will investigate grasp planning for edge-rolling: designing the end-effector and choosing grasps that enable stable edge-rolling. We will model edge-rolling as a quasidynamic process in that dynamic loads are necessary to counterbalance the non-jamming, applied forces, but the process is highly overdamped so that accelerations of the object do not yield significant momentum.

In our approach, objects of interest are thus modeled as right circular cylinders. We are interested in developing a robotic technique for edge-rolling, particularly using very simple end-effectors—in essence, single rigid body end-effectors with no internal degrees of freedom (DOF), which can also be seen in our previous work on object caging, fixturing, picking-and-placing [3], [7]. The lack of mobility in those simple end-effectors can render robotic edge-rolling very practical yet challenging at the same time.

When simply holding the object, it is sufficient to have an end-effector that can make two point contacts with friction at A, B produced by the end-effector and another frictional contact at G on the ground surface. In [28], it is examined how to obtain force-closure grasps with three frictional contacts. This idea can be realized using, for example, an end-effector with two parallel fingers as illustrated in Fig. 2(a). Note that the relative configuration of the fingers can be fixed (no internal mobility) and that all the contact forces are unilateral. We will consider how to adapt the effector shapes and the grasps shown in Fig. 2(a) to successfully realize the desired contact mode for edge-rolling: rolling the object on the ground surface and, in the meantime, sliding the object on the contacts with the end-effector such that the relative configuration between the end-effector and its robot body can remain fixed. In taking advantage of such nonprehensile grasps, our resulting edge-rolling technique can thus be considered as a form of in-hand manipulation, which still remains as a great challenge.

IV. END-EFFICTOR SHAPE DESIGN FOR EDGE-ROLLING

This section presents our end-effector design approach to realizing stable edge-rolling.
A. Local and Global Geometry

When it comes to transitioning from holding (Fig. 2(a)) to edge-rolling, the three frictional point contacts that work well for holding the object are not effective in that it can be hard to maintain force equilibrium in the desired contact mode (Fig. 2(b)). For example, if one supposes that the weight of the object is negligible, then the three contact forces can be in static equilibrium only in the case they are necessarily coplanar, according to screw theory [29]. This is almost impossible here in the sense that the direction of the frictional contact wrenches at the end-effector cannot be controlled while the object is sliding on the end-effector.

![Diagram](https://via.placeholder.com/150)

Fig. 3. (a) Four point contacts $A_1$, $A_2$, $B_1$, and $B_2$ made by the polyhedral end-effector. (b) Two point contacts $A$ and $B$ made by the end-effector with the curved contact surfaces. In the panels, contact $A_1$ is antipodal to $B_1$ as seen in the direction of the axis of the object.

Our approach to making the end-effector (that is, the two point contacts $\{A, B\}$ that are antipodal as seen in the direction of the axis of the object) more suitable for stable edge-rolling is to consider how to impart non-degenerate contact wrench cones even when the object is sliding on the end-effector. This can be achieved by fixing the local geometry around the two contacts by incorporating (1) additional contacts and (2) surface curvature effects. For example, Fig. 3 is illustrating scenarios in which two additional contacts are added (Fig. 3(a)) and the object is in contact with the concavity of the curved effector surfaces (Fig. 3(b)), as seen in the direction of the axis of the object.

Additional contacts can produce contact wrenches based on the first-order effects of the additional contact normals. For example, in Fig. 3(a) there are now four contact normals at $A_1$, $A_2$, $B_1$, and $B_2$ that can induce contact wrenches regardless of contact modes (in Fig. 2, only two contact normals at $A$ and $B$). Due to the concavity at the contacts, the object in Fig. 3(b) cannot move tangentially at all into the curved surface. Therefore, the effects of the concavity of a smooth contact surface (in other words, the second-order geometric, surface curvature effects [30]) can also be understood using multiple contact wrenches in the direction of, and orthogonal to, the contact normal, regardless of contact modes. Note that in practice, elastic deformation contact models are needed to explain the additional tangential contact wrenches induced by the second-order effects [30]. Therefore, the object in contact with the curved effector may need to be dislocated from the nominal contact position to induce sufficiently large contact wrenches.

By virtue of these extra design features, the contact wrenches incorporating the additional contact normals or the curvature effects can span (1) all the forces perpendicular to the object’s axis (force-direction closure [31] except for the direction of the object’s axis) and (2) all the pure torques (torque-closure [31]) along with the frictional contact at $G$, with neither friction effects nor dependence on contact modes between the end-effector and the object. We shall explain how to address the incomplete force-direction closure using active control in Sec. VI-B.

In terms of global geometry, we intend to fabricate the end-effector as a single rigid body modeled as a closed, two-dimensional manifold with a genus such that objects in different sizes can be addressed in the hole. Our end-effector, having no DOF, will then be operated in a passive manner, interfacing the wrist of a manipulator and the object. This is a conservative approach, compared with the potential role of dexterous in-hand manipulation by the human operator (Fig. 1), but it has the potential to be more practical. Figs. 7 and 10 show our two- and four-contact end-effectors realizing the design approach here. They all can accommodate objects in various sizes.

B. Modeling for Grasp Planning

For planning purposes, our end-effector, modeled as a single rigid body with no internal DOF, will further be abstracted again as two rigidly connected point contacts that are antipodal as seen in the direction of the axis of the object. Whether sliding occurs or not, each of the two contacts is able to exert a planar cone of wrenches by the effects of the design features (the additional contact normals and the curvature effects) discussed in Sec. IV-A. See Fig. 4(a).

Our four-contact end-effector (Fig. 3(a)) actually makes the two contact pairs $(A_1, A_2)$ and $(B_1, B_2)$, and there is a question of whether this is equivalent to such an antipodal contact pair. The resulting forces are assumed to act at $A$ on arc $A_1A_2$ ($B_1B_2$); for example, $A$ can be $A_1$, $A_2$, or the midway point between $A_1$ and $A_2$ on the perimeter. The approximation improves as the distance between $A_1$ and $A_2$ ($B_1$ and $B_2$) gets smaller. For an object that is a rigid line segment, any modeling errors will vanish. Therefore, for relatively slender objects (for which edge-rolling can be an effective way of handling), the modeling errors can be insignificant. The planar wrench cone at $A$ ($B$) is spanned by the unit wrenches parallel to the contact normals at $A_1$ and $A_2$ ($B_1$ and $B_2$). The aperture of the wrench cone, denoted $\psi_A$ ($\psi_B$) in Fig. 4(a), is thus equal to the angle between the contact normals at $A_1$ and $A_2$ ($B_1$ and $B_2$).

Our ellipse-shaped, two-contact end-effector (Fig. 3(b)) can indeed make such an antipodal contact pair. The geometry of the planar wrench cone can be determined by linearizing the shape of the effector as a polygon and following the same procedure as in the previous paragraph. To be more rigorous, elastic deformation has to be taken into account as discussed in Sec. IV-A, but we assume that it is negligible. More thorough dynamics analysis is left as future work.
V. GRASP SYNTHESIS FOR STABLE EDGE-ROLLING

According to our model presented in Sec. IV-B, a grasp is defined as a triple \((h, \theta, \phi)\) in which \(h\) is the distance from the bottom face to the end-effector, \(\theta\) is the angle between the ground surface and the axis of the object, and \(\phi\) is the angular position of the contacts on the circular base of the object (Fig. 4(b)). We here discuss how to find grasps that are secure and capable of edge-rolling—grasps that are able to realize the desired contact mode (sliding between the object and the end-effector, and rolling between the object and the ground surface) without losing the object.

A. Grasps That Are Secure

In order to find grasps that can securely hold the object during edge-rolling, we search for grasps that can indeed fulfill the promise of the design features: grasps in force-direction closure, except for the direction of the object’s axis, and torque-closure with the three contacts at \(A\), \(B\), and \(G\) (Fig. 4(a)). The contact wrenches at \(G\) form a friction cone. The contact wrenches at \(A\) and \(B\) form planar wrench cones induced by the design features as explained in Sec. IV-B; they do not depend on friction such that the closure properties can be independent of friction and contact modes at \(A\) and \(B\). The closure properties can be formulated as an optimization problem (linear programming) as in [32].

To visualize the set of the secure grasps, we performed numerical simulations. Data points were randomly sampled in \(h\theta\phi\)-space and the closure properties were checked by solving the linear programming problem for each data point. Fig. 5 shows the point cloud of the secure grasps on a cylindrical object. It can be seen that the absolute value of \(\phi\) is upper bounded. As the grasp parameter \(h\) increases, the set of allowable \(\phi\) and \(\theta\) expands. It can also be seen that the larger the friction at \(G\), the higher the upper bound on the absolute value of \(\phi\).

B. Grasps That Are Capable of Edge-Rolling

Now we examine how to find grasps capable of edge-rolling, in the set of the secure grasps. The resulting grasps will realize the desired contact mode (sliding contacts between the object and the end-effector, and a rolling contact between the object and the ground surface) in a quasidynamic manner. The application of a quasidynamic analysis here is justified by considering our edge-rolling technique can be thought of as a highly overdamped dynamical process. It is not fully dynamic in that accelerations do not integrate into significant velocities, but quasistatic analysis might not be expressive enough in that dynamic loads (or inertial forces) are necessary to counterbalance the non-jamming, applied forces. This situation is similar to the well-known peg-in-hole insertion task, an exemplary quasidynamic process.

The closure properties of the secure grasps allow us to perform a planar analysis on the plane of the bottom face of the object in which only \(\phi\) does matter in terms of configuring grasps. Fig. 6 explains how to generate the acceleration that can roll the object to the right (clockwise) in dynamic equilibrium. The figure features frictional contact forces at \(A\) and \(B\) in order to understand how to overcome the friction and make edge-rolling possible by changing \(\phi\). Thus, contacts \(A\) and \(B\) are able to impart only the wrenches \((\mathbf{w}_A\) and \(\mathbf{w}_B)\) lying on the edge of the friction cone consistent with the direction of motion. It is a conservative approach in that the contact wrenches induced by the design features are not taken into account.

The dynamic load \(\mathbf{f}\) due to rolling without slipping in the \(x\)-direction can be obtained by finding the dual transform [4] of the acceleration center [4]. \(\mathbf{f}\) is parallel to the ground surface and tangent to the object if we select the unit of length to be the object’s radius. According to the formalism of moment labeling [4], the “−” labeled gray sets represent the composite wrench cone of the dynamic load \(\mathbf{f}\) and the negated contact wrenches \(-\mathbf{w}_A\) and \(-\mathbf{w}_B\). Then the sets include all wrenches at \(G\) that would lead to the desired contact mode (sliding at \(A\), \(B\) and rolling at \(G\)). The diagram can be interpreted as follows. When \(\phi\) is too small (Fig. 6(a)), there is no external wrench \(\mathbf{w}_{ext}\) at \(G\) belonging to the composite wrench cone (that is, not intersecting the gray set, and making a negative (−) moment about each point in the “−” labeled
In the direction of its axis. The panels show the positions of the contacts $A$ and $B$, and the wrenches acting on the object (the arrows) in case $\phi$ is (a) small and (b) large. Note that at $A$ and $B$, the wrenches are negated ($-w_A$ and $-w_B$). $w_{ext}$ leads to the desired contact mode in (b), but not in (a).

$w_{ext} \in \text{pos}(\{f, -w_A, -w_B\})$

Or equivalently, the contact wrenches $w_{ext}$, $w_A$, and $w_B$ can be combined to produce the dynamic load $f$.

Therefore it can be seen that $\phi$ should be lower bounded in order to maintain quasidynamic equilibrium in the desired contact mode. In Fig. 6, this happens in case $-w_B$ can make a positive moment about $G$. It can also be seen that the lower bound depends on the friction at $A$ and $B$. For example, in case the friction coefficient at $B$ is $\mu_B = 0.2$, the lower bound on $\phi$ is computed to be $22.61^\circ$. The larger the friction cone at $A$ and $B$, the larger the lower bound on $\phi$. The conservative analysis here clearly shows the advantage of adjusting $\phi$, particularly in the case of using end-effectors taking advantage of the second-order curvature effects (such as the ellipse-shaped one in Figs. 7 and 10) whose mechanical behavior can be difficult to model.

C. Conclusion: How to Grasp and Regrasp

In order for stable edge-rolling to happen with the right contact mode, $\phi$’s lower bound, that will enable rolling (discussed in Sec. V-B), should indeed be less than its upper bound for the closure properties (discussed in Sec. V-A). As discussed above, low friction at $A$, $B$ and high friction at $G$ will facilitate this; in contrast, the combination of a “sticky” end-effector and “slippery” ground can render edge-rolling impossible. We take the intersection of the conditions to get the collection of feasible (that is, both secure and capable of edge-rolling) grasps. One viable approach to choosing a grasp is elaborated below:

Strategy for Choosing a Grasp: First, $\phi_{lb}$ (the lower bound on $\phi$) can be found by the quasidynamic analysis in Fig. 6. Second, $h$ is chosen such that the upper bound on $\phi$ (see Fig. 5(c)), denoted $\phi_{ub}$, is greater than $\phi_{lb}$. Third, $\phi$ is chosen such that $\phi_{lb} \leq \phi \leq \phi_{ub}$. Fourth, $\theta$ is chosen such that it is less than its upper bound given $h$ (see Fig. 5(b)).

It is possible to change the grasp parameters $h$, $\theta$, and $\phi$ (in other words, “regrasping”) in a continuous manner without losing stability because the set of the secure grasps can be represented as a connected space with a single component (recall Fig. 5). Useful regrasping operations include changing the sign of $\phi$ for switching the direction of edge-rolling and $\theta$ for tilting the object. $\theta$ and $\phi$ can be changed by making use of the mobility of the arm to which our passive end-effectors are attached since the end-effector and the object move together in unison (see Figs. 8(a) and (b)). Although our end-effector lacks any controllable degrees of freedom to directly change $h$, it can be changed by appropriately steering the object (see Figs. 11 and 12).

One way to further facilitate edge-rolling, given $\phi$, is to increase $\theta$ and decrease $h$. As $\theta$ is increased, it is possible to balance the force of gravity with smaller end-effector forces because the moment of gravity about $G$ would decrease. Similarly, it takes less effort to balance ground reaction wrenches as $h$ is decreased. These all contribute to reducing internal forces between the object and the end-effector. However, there is a trade-off between ease of edge-rolling and grasp stability: as the grasp parameter $h$ ($\theta$) decreases (increases), the set of the secure grasps shrinks as can be seen in Fig. 5. If $h$ ($\theta$) is too small (large), the moments of all the contact forces can be unilateral and thus the object might not be in torque-closure.

One side effect of our approach to edge-rolling with the secure grasps is that, as long as the grasp is maintained, the other contact mode with a sliding contact on the ground and rolling (in essence, fixed) contacts on the end-effector can also happen. Whether or not the object will actually edge-roll depends on the magnitude of the internal forces. This can be formulated as a complementarity problem and solved for each of the contact modes. An example can be seen in [2]. However, the question cannot be fully addressed by such a rigid body mechanics approach, which can result in inconsistency or indeterminacy. A compliant contact model can make the analysis more complete.

VI. IMPLEMENTATION AND EXPERIMENTATION

In this section, we demonstrate the soundness of our grasp planning for stable edge-rolling using an industrial robot arm and a wheeled mobile robot equipped with our zero-mobility end-effectors.
A. Edge-Rolling with a Conventional Manipulator

Using a seven-DOF Rethink Robotics’ Sawyer robot arm, we demonstrate that stable edge-rolling can be realized with our end-effector design approach and grasp planning. See Fig. 7. Two types of end-effectors following the design approach presented in Sec. IV-A were 3D printed: four- and two-contact end-effectors. When viewed in the direction of the axis of the object, the four-contact effector looks like a rhombus, making contact with the object on each of its edges. The ellipse-shaped, two-contact end-effector is supposed to make two contacts with an object at the end points of its semi-major axes. The curvature around the contact points provides the second-order effects. The Sawyer is controlled to edge-roll the axis of the object, the four-contact effector looks like a rhombus, making contact with the object on each of its edges. The ellipse-shaped, two-contact end-effector is supposed to make two contacts with an object at the end points of its semi-major axes. The curvature around the contact points provides the second-order effects. The Sawyer is controlled to edge-roll objects on a small treadmill because of the limited size of its workspace.

Initially, a cylindrical object is in the upright configuration, and the Sawyer arm is away from the object. If coefficients of friction\(^1\) are assumed to be \(\mu_A = \mu_B = 0.2\) (between plastic and metal at contacts A and B), the lower bound on \(\phi\) is computed to be 22.61° as discussed in Sec. V-B. If \(\mu_C = 0.7\) (between metal and concrete at contact G) and the aperture of the wrench cones at A, B is 100° (this is the angle between the two adjacent contact normals that our four-contact end-effector can make on an object whose diameter is 1.9cm), then \((h, \theta, \phi) = (0.13m, 45^\circ, 45^\circ)\) can be a legitimate target grasp because it lies in the space of the secure grasps (as in Fig. 5) and \(\phi > 22.61^\circ\) (the lower bound). The arm is then position controlled to bring the object into the target grasp (Fig. 8(a)):

- **Phase I Object tilting**: The robot is first controlled to cage the object in the hole of the end-effector. \(h\) is chosen at this point. Then the robot tilts the object to the desired \(\theta\) value by following a position trajectory in which the path maintains quasistatic stability through in-hand manipulation even without gripper mobility, as presented in our previous work [3].
- **Phase II Adjusting \(\phi\)**: The robot then rotates its end-effector about the axis of the object up to the desired \(\phi\) value. Due to the closure properties of the grasp, the object may also rotate with the end-effector (it may thus roll on the ground surface). The arm is also controlled to compensate for the relocation of the object.

\[\begin{align*}
\phi &= \mu_A - \mu_B \\
\phi &= \mu_C \sqrt{\frac{h}{\cos \theta}}
\end{align*}\]

\(^1\)These values are from sources on engineering practice so the values are approximate.
success rate is 76/82 = 92.7%. The complement of this set has success rate 37/125 = 29.6%. Note that, however, if the angle between the two adjacent contact normals decreases (recall that this angle was 100° in our four-contact end-effector), the success rates can drop significantly in particular for the grasps with large φ. The effectiveness of the second-order curvature effects can be assessed by comparing the outcomes of the two- and four-contact end-effectors: our result shows that the two-contact fails 25% more out of 60 trials.

Furthermore, our robot is also able to switch the direction of edge-rolling through regrasping. In Fig. 8(b), the robot was controlled to regrasp from \((h, \theta, \phi) = (0.13m, 45°, 45°)\) to \((h, \theta, \phi) = (0.13m, 45°, -45°)\). The treadmill was then advanced in the opposite direction, and the object was able to roll counterclockwise (clockwise before regrasping); see the video attachment. To further verify the robustness of our edge-rolling technique, the robot was controlled to perform edge-rolling along a 36cm tall vertical half-pipe track (Fig. 8(c)). Here the arm was position-controlled in a feedforward manner with no feedback to follow a trajectory on which the relative configuration between the end-effector and the tangent plane to the half-pipe track at the contact \(G\) remained constant. In other words, nominally \((h, \theta, \phi) = (0.13m, 45°, 45°)\) on the trajectory; the grasp was chosen for the four-contact effector by following the strategy specified in Sec. V-C. It was possible to successfully (10 successes / 10 trials) edge-roll the object from the bottom of the track, where the normal at \(G\) is antiparallel to gravity, to the top, where the normal is parallel to gravity (see the video attachment).

**B. Long-Range Edge-Rolling Manipulation**

We demonstrate long-range edge-rolling by a modular mobile manipulator whose workspace is not constrained by joint limits like the Sawyer. The robot is assembled with CKBot V3 modules [33]. It has a differential-drive and a one-DOF arm mounted on top. The two- and four-contact end-effectors can be fixed to the arm (Fig. 10(a)).

![Fig. 10. (a) Our mobile robot with three servos (M1, M2, and M3) and an effector-arm substructure on top of M2. M1 and M2 drive the robot in a differential-drive manner. M3 is able to rotate the effector-arm substructure about the axis perpendicular to the ground (see the video attachment). (b) \(\gamma\) denotes the difference between the headings of the object and the mobile base. The object may escape from the end-effector as \(\gamma\) builds up.](image)

The one-DOF mobility of the arm is used for steering the object about an axis perpendicular to the ground surface. This active steering capability is the key to edge-rolling long distances in a robust manner. If the heading of the object is not aligned perfectly with the direction of the motion of the base during edge-rolling (that is, non-zero \(\gamma\) in Fig. 10(b)), the object may end up sliding down or up on the end-effector surface while rolling on the ground. This is because of the nonprehensile nature of our grasp in incomplete force-direction closure. Suppose that the mobile base in Fig. 10(b) moves in the positive \(\gamma\)-direction. Positive (negative) \(\gamma\) results in the object sliding up (down). As seen from the end-effector, the object moves along a helical path, like the motion of a screw. This can result in loss of the grasp if not addressed (Fig. 11).

![Fig. 11. For a small (\(\gamma = 10°\)) misalignment in object heading the grasp can lead to the object sliding out of the grasp and the track of the treadmill (down in photograph).](image)

The robot is able to measure the relative translation of the object and the end-effector by receiving feedback from a motion capture system. An integral (I) controller was implemented to correct the error and adjust the relative orientation between the mobile base and the object-effector-arm system:

\[
u(t) = K_i \int_0^t (h(\xi) - h_0) d\xi
\]

\(u(t)\) is an angular position command for the steering arm. It is proportional to the cumulative error in the grasp parameter \(h\). If the value is positive (negative), the arm is controlled to turn counterclockwise (clockwise). The value of \(u(t)\) was limited to the range \([-17°, 17°]\). If the arm is allowed to steer more aggressively, we empirically observe that it can jeopardize the control of the object.

Fig. 12 illustrates a sample path. With active steering on, the amount of the unwanted translation was bounded and the robot was able to edge-roll the object and travel around the square at least twice, 15.9m or 265 times the perimeter of the object. The nominal grasp here was also chosen by following the strategy specified in Sec. V-C. With active steering off, the object translates off the grasp, traveling only 0.3m. See the video attachment. We believe the minor alignment errors (small \(\gamma\)) during the experiment allow for the simple, purely feedback I-controller to be effective. A model predictive controller, taking the model of dynamics into account, may be worth investigating for more responsive active steering.

**VII. Conclusion**

This paper presents grasp planning for robotic edge-rolling with zero mobility, passive end-effectors that can be fabricated as a single rigid body. The generated set of feasible grasps takes into account the closure properties and quasidynamic equilibrium. Successful edge-rolling was demonstrated with a conventional manipulator arm and a modular mobile platform...
on a treadmill, the ground surface, and a U-shaped vertical half-pipe track.

This work establishes the first steps towards more practical and complete robotic edge-rolling manipulation. Possible directions for future work include incorporating more sophisticated models of contact/friction, improving the steering control capability to better hold the object, implementing fully autonomous roll-and-place manipulation in the unstructured environment, and generalizing into a wider range of objects such as prismatic objects other than cylinders.

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