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Enhanced Robotic Cleaning with a Low-cost Tool Attachment

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Abstract— **Robots that can reliably manipulate human tools can do a diverse range of useful tasks in human environments. However, these tools are often difficult to manipulate, particularly given force requirements for applying the tool. This is often due to the mismatch between the robot's gripper and the tool handle designed for human hands. In this paper, we present the design of a low-cost universal tool attachment that makes the tool *gripper-friendly*. We demonstrate the performance gain provided by the attachment on 10 different tools in the three stages of tool use: *grasping* the tool, *applying* the tool, and *placing* the tool. Our experiments demonstrate that the attachment performs significantly better in all three stages of tool use.**

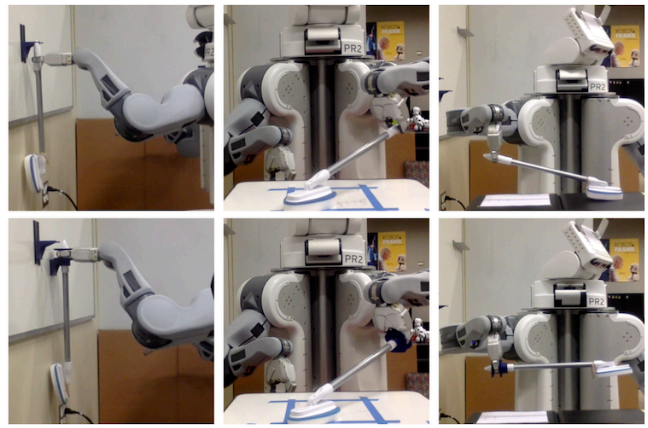

Fig. 1. The PR2 robot grasping, applying, and placing a human tool. The top row shows the use of the original tool and the bottom row shows the use of the same tool fitted with our universal tool attachment, Griple, that allows a more stable grasp and better force transfer through the tool.

I. INTRODUCTION

Structured environments, such as factories, enable robots to do impressive, high-precision tasks with high reliability. These environments are explicitly designed around the robot to simplify perception and manipulation problems. As robots move into unstructured environments designed for humans, they are faced with significantly more challenging versions of these problems. Although robotics research is making great strides in dealing with these problems, the state-of-the-art is far from being practical. This indicates a trade-off: the more structure we can add to the environment to make it robot-friendly, the more complex, reliable, and robust the tasks achievable in that environment are. Our approach is to modify human environments so as to induce additional structure that simplifies the robot's task, but does not disrupt human activities. We believe that this approach makes a range of useful tasks practical. In this paper we apply this approach to robotic tool use for cleaning.

Cleaning has long been considered an undesirable chore that is well-suited for robots [19], [1], [7]. There have been commercial successes with special-purpose robots designed for a particular cleaning tasks (e.g. vacuuming, pool cleaning); however, there are many human cleaning tools that have not been replicated with such robots. Instead, research on robotic tool-use aims to make general-purpose robots manipulate human tools [21], [12], [16]. One of the key challenges faced in robotic tool-use is the mismatch between the robotic gripper and the tool handle. Human tools are ergonomically designed to fit human hands. There have been numerous efforts to design multi-finger robotic hands that mimic human hands [8], [4], [2]. However, even with state-of-the-art sensing and control, these hands are far from achieving human-level dexterity that would enable powerful tool use. Furthermore, such hands are expensive.

Instead, we propose modifying human tools to match a simple and low cost robotic gripper. In this paper, we present the design of a universal tool attachment, named *Griple* (*Grip*per Hand*le*), that simplifies the grasping problem and enables a stable grasp even in the face of external forces applied on the tool. We demonstrate the performance gain provided by Griple with 10 different tools, in three stages of tool-use, through multiple task performance metrics. Our experiments indicate that Griple provides significant improvements across all metrics and allows human-level cleaning through a simple Programming by Demonstration (PbD) system.

In the following we present the design of our universal tool attachment, the Griple (Sec. II), and our PbD system for tool use (Sec. III). In Sec. IV we describe our experiments and in Sec. V present our results, followed by a related work on grasping, tool use, and gripper design (Sec. VI).

II. DESIGN OF THE GRIPLE

We start by articulating our design constraints and we describe the design of Griple (Fig. 3), which was produced based on these constraints.

A. Robotic platform and gripper

The robot platform used in this work is PR2 (Personal Robot 2) which is a mobile manipulator with two 7 Degree-of-Freedom (DoF) arms and an omnidirectional base (Fig. 1).

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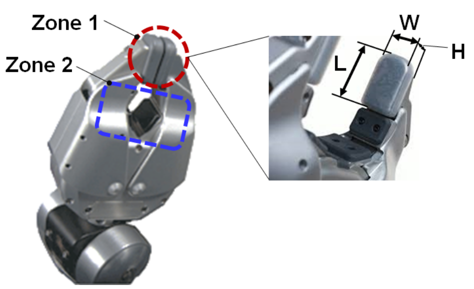

Fig. 2. The gripper of a PR2 robot. *Top right:* The zoom-in view showing the dimension of the finger pad in Zone 1.

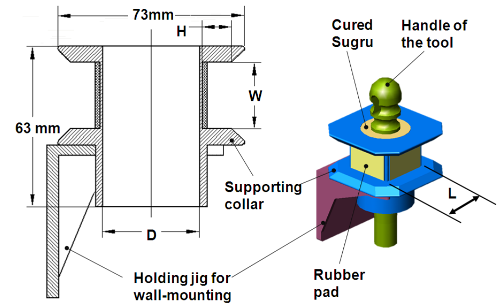

Fig. 3. 3D drawing of Griple showing key dimensions (W: width, H: height, and L: length of the finger pad; D: inner diameter).

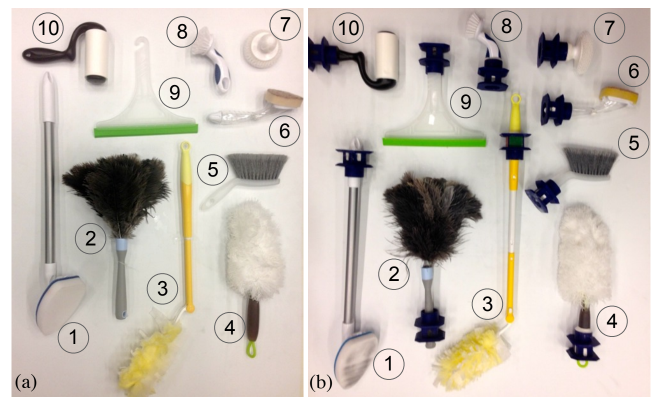

Fig. 4. Tool set with number references: (a) *original* un-altered tools, (b) *modified* tools fitted with a *Griple*.

Each arm has a 1 DoF back-drivable gripper and can carry up to 2.2kg. The passive spring counterbalance system in PR2's arms makes them naturally gravity-compensated, giving users the ability to physically move the arm within its kinematic range. This supports our PbD approach (Sec. III) in which tool grasping, application and placing actions are programmed through kinesthetic demonstrations.

The PR2 gripper has two grasping zones (Fig. 2) allowing different grasp types. When actuated, the two fingertips (zone 1) move towards or away from each other while remaining parallel. This mechanism allows *precision grasps* in which the grasped object is contacted only at the fingertips. The opening between the angled finger pads (zone 2) increases the throat capacity of the gripper to avoid unwanted collisions between the gripper and the grasped object during a precision grasp. The geometry of this opening changes as the gripper opens and closes. This allows *power grasps* in which the gripper encloses the object making contacts at multiple points around the object.

B. Tool set

In this paper we focus on cleaning tools; however, our design could be used for other human tools with handles (*e.g.* repair tools or kitchen tools). For our experiments we chose 10 representative tools shown in Fig. 4. Tool 1 is a sponge that allows removing moisture or stains off of flat surfaces. Tools 2, 3, and 4 are dusting tools with different properties. Tool 5 is a hand tool used for sweeping away dust and coarser dirt off of a surface. Tools 6, 7, and 8 are scrubbing tools in different forms. Tool 9 is a *squeegee* that allows removing moisture and dirt off of a flat surface with high precision. Tool 10 is a rolling lint remover that allows removing lint stuck on fabric surfaces.

C. Design space and constraints

1) Attachment surface: In order to make Griple universally fit a large range of human tools, we consult human factors guidelines for tool handle design. Most cleaning tools involve humans using a power grasp to allow application of necessary force and precise control. As a result they mostly have cylindrical handles of diameter ranging between $32mm$ and $51mm$ (1 1/4 to 2 inches) to fit the human hand [14]. Accordingly, our design involves an inner cylindrical hole that is $D = 38mm$ in diameter, to enclose the handles of most cleaning tools; including all of the ones in our tool set (Sec. II-B). We propose using Sugru silicone rubber[1] for permanently securing the position of the Griple onto the handles of the cleaning tools.

2) Grasping surface: The Griple is aimed at supporting precision grasps with the parallel fingertips (Sec. II-A). To achieve the maximum contact surfaces between the attachment and the fingertips, the outer layer of Griple has a rectangular prism shape symmetric around the tool handle axis. The size of the rectangular prism (L and W) is chosen based on the dimensions of the robotic gripper (Fig. 2).

3) Force requirements: Applying a tool requires applying a force onto a surface with the tool. This force needs to be transferred from the tool handle to the application surface, as illustrated in Fig. 5. When a cleaning tool is pushed against a surface, the torque (M_p) generated near the gripper will tend to rotate the cleaning tool around the grasping point. Although the induced friction forces can contribute to counteracting torques (M_f), their magnitudes are bounded by the diameter of the friction cone and by the contact areas between the tool and the gripper.

Our design addresses this issue in two ways. First, it stabilizes the grip with extra supporting forces N_1 and N_2

[1]FormFormForm itd, Hackney, London. `http://www.sugru.com/`

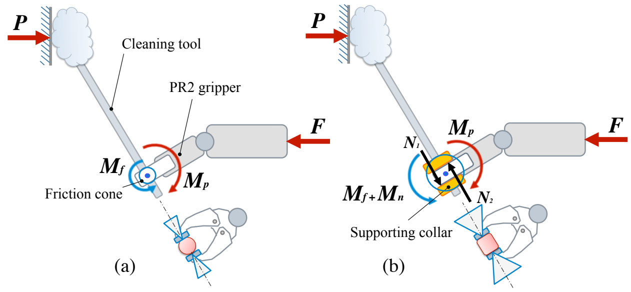

Fig. 5. Force analysis of a robot with parallel gripper performing manipulation tasks. (a) Robotic manipulation with an unaltered tool. The diameter of the friction cone is bounded due to the limits of contact areas. (b) Extra supporting forces (N_1 and N_2) and increased fiction forces are available for a more stable grasp after the same tool is equipped with our proposed tool attachment.

provided by *collars* on both sides of the finger tip. These forces simultaneously increase the pushing force P and create a torque M_n around the grasp point that counter balances the torque M_p. Second, the flat grasping surfaces provide maximum contact areas, hence increasing the resistance friction. This results in higher M_f for resisting the torque M_p.

D. Additional features and specifications

As shown in Fig. 3 the supporting collars on Griple have tapered edges. These allow offset-tolerance during grasping by allowing the gripper to slide in when the initial contact is offset. In addition to the Griple, we designed a wall-mounting jig on which tools fitted with a Griple can hang vertically.

The total weight of the Griple is around 61 grams and the weight added to the tool can vary depending on the amount of Sugru used for attachment. The location of the Griple on the tool can be chosen to be around the handle intended for human usage to ensure that the functionality is preserved. However, alternative attachment positions, which preserve the option of manual handling, are also possible. Except for the rubber pads on the grasping surfaces, all the parts of Griple were 3D printed. Printing one Griple and jig took approximately seven hours[2] and the total cost was less than $10.

The set of tools fitted with a Griple are shown in Fig. 4(b) and their specifications (total weight and length of the moment arm between the handle/griple and the application surface) are listed in Table I.

TABLE I
SPECIFICATIONS OF THE ORIGINAL AND MODIFIED TOOLS.

	Weight (gram)		Length (cm)	
	Original	Modified	Original	Modified
Tool 1	192	240	62	62
Tool 2	100	162	40	40
Tool 3	106	164	80	80
Tool 4	96	170	38	38
Tool 5	74	138	23	23
Tool 6	46	92	24	24
Tool 7	26	96	7	12
Tool 8	74	126	16	18
Tool 9	92	170	24	25
Tool 10	116	170	21	21

III. Implementation of Tool-use Actions

Using a tool to perform cleaning tasks autonomously requires the robot to (i) identify and localize the tool, (ii) grasp and possibly re-grasp the tool, (iii) apply the tool on the surface that needs to be cleaned with a tool-specific strategy, and (iv) place the tool back. The Griple is intended to simplify or aid all of these problems; however, in this paper we focus on tool manipulation and leave out perception problems. Nonetheless, we emphasize that a distinct and uniform attachment on tools, such as the Griple, has the potential to greatly simplify the identification and localization of the tools.

The robot's actions for grasping, applying and placing tools were programmed by demonstration using an open source system described in [9]. With this system, actions are programmed by creating an empty action and adding key poses to it. Poses are specified by physically moving the robot's arms to a desired configuration (while they are in a gravity compensation mode) and changing the robot's gripper states (opening or closing). To execute an action, the robot simply moves through the saved poses. All commands to the robot are given verbally and are from a fixed set of possible commands, such as "Save pose," "Execute action," or "Open right hand." The system allows poses to be relative to landmarks in the environment (*e.g.* the tool or the table) that can be localized by the robot. This allows the actions to be generalizable to novel situations in which the setup might be different. In this paper this functionality was not used as the perception of the tools was not yet implemented. Instead, we replicated actions by accurately placing the tools and the cleaning surfaces at the same initial positions during demonstration and execution.

A. Grasping and placing

Grasping actions involved the robot opening its gripper, moving it to a pre-grasp pose near the tool, approaching the tool, closing the gripper, and moving the tool away from its initial position. For original tools the grasp point was chosen around the handle. For tools that had a Griple the grasp point was as intended by the design (Sec. II). Placing actions involved the inverse of the grasping sequence. Our approach required a different grasping and placing action to be programmed for each of the original tools. On the other hand, the same grasping and placing actions were used for all tools that had a Griple.

B. Tool application

Tool application actions involved replicating tool trajectories tested by an experimenter prior to programming the

[2]The 3D printer used was a Printing Dimension BST 768 by Stratasys Corp., Eden Prairie, MN.

TABLE II

TOOL APPLICATION TESTS BY TOOL TYPE.

Tool type	Tool application test
Sponge (Tool 1)	remove marker stains on a whiteboard surface
Dusters (Tools 2, 3, 4)	dust off talc powder off of a paper surface
Sweeper (Tool 5)	sweep away talc powder off of a paper surface
Scrubbers (Tools 6, 7, 8)	displace small magnets on a metal surface
Squeegee (Tool 9)	remove small magnets off of a metal surface
Lint remover (Tool 10)	remove synthetic fibers off of a fabric surface

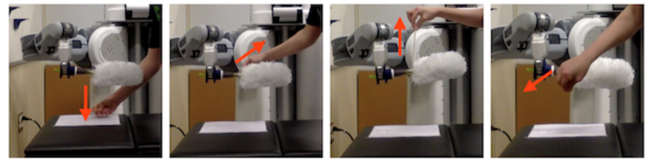

Fig. 6. Snapshots from the grasp stability tests in which external forces are applied on the tool by pulling an elastic band attached to the tool near its application surface.

robot. A different tool application action was programmed for each tool. To isolate different problems that occur during different phases of tool use, the tool application actions were considered independently from the grasping and placing actions. For this reason, all tool application actions started with the tool being handed to the robot by an experimenter. The grasps on original tools were made as stable as possible; hence, in some cases, different from the grasps that were achievable with the programmed grasping actions.

IV. EVALUATION

We demonstrate the performance gain provided by the Griple for our set of 10 representative tools (Fig. 4) in three experiments addressing the different stages of tool use (Sec. III): (i) *grasping* the tool, (ii) *applying* the tool, and (iii) *placing* the tool[3]. In each experiment, we compare the robot's performance in two conditions: (a) using *original* tools, versus (b) using *modified* tools fitted with a Griple. To ensure a fair comparison, we experimented with programming by demonstration to find the best possible grasp and trajectories for both conditions, in all three experiments. While we were able to use the same programmed action for all tools with a Griple, we needed to program a unique action for each original tool, in each experiment.

A. Experiment 1: Tool grasping

The first experiment investigates how the Griple impacts the robot's ability to successfully grasp and take control of a tool, as well as how stable the grasp is. We consider two situations in which the tool is (i) hanging vertically or (ii) lying horizontally on a flat surface (Fig. 7). For each tool in each situation, the robot performs the grasping action programmed by the experimenter (Sec. III) using zone 1 of the PR2 gripper (Fig. 2). The grasp is deemed *successful* if the tool remains in the robot's gripper for 5 seconds after it stops moving. The grasp is deemed *stable* if the tool remains in the same configuration when subjected to an external force. We ensure consistent application of external forces using a lightweight elastic band tied on the tool near the application surface. The rubber band is pulled in four directions, parallel and normal to the grasping surfaces on the fingertip, up to a 100% extension of the elastic band (Fig. 6). If the tool configuration changes in response to any of these pulling tests, the grasp is considered unstable. We repeat each grasp three times and count the number of successes.

[3]See video for sample trials at `http://youtu.be/wiZOTpRkB7Y`

B. Experiment 2: Tool application

The second experiment investigates how the Griple improves the application of a tool onto flat surface for cleaning it. The success of each cleaning tool was measured in terms of the percentage of the target surface on which the tool is successfully applied. Successful application depends on the tool type; therefore, we created a different test for each tool type, as summarized in Table II. To isolate this experiment from Experiment 1, tools were handed to the robot by the experimenter in the most stable grasp possible. For original tools, this involved using zone 2 (Fig. 2) of the PR2 gripper in certain cases (when the size and geometry of the handle are well suited). The robot was programmed to replicate a tool trajectory tested by an experimenter on each of these tasks and achieved 100% success when applied by the experimenter. Tasks were performed on a $20{\times}20$ cm flat cleaning surface. Before and after each tool application trial, a picture of the cleaning surface was recorded, as show in Fig. 8. The percentage of the surface that was successfully cleaned was calculated by fitting a $10{\times}10$ grid on these pictures and counting the number of cells that were successfully cleaned.

C. Experiment 3: Tool placement

Finally we tested the robot's ability to successfully place a tool back to its initial configuration. As in Experiment 1, we considered hanging the tool vertically, as well as placing the tool onto a flat surface. The success of each placement task was measured by how closely the final configuration of the tool (after being placed) matched its initial configuration. The trial was considered *successful* if the difference was less than $.5cm$; *partially successful* if the difference was between $.5cm$ and $2.5cm$; and *failed* otherwise. In the vertical case, a failure corresponded to the tool being dropped on the floor.

V. RESULTS

A. Experiment 1: Tool grasping

Table III presents the *success* in grasping the original and modified tools. We see that the robot was able to grasp tools that have a Griple with 100% success rate both when they were hanging vertically and lying horizontally on a surface.

TABLE III

NUMBER OF SUCCESSFUL GRASPS IN EACH TEST OUT OF 3 TRIALS.

	Vertical		Horizontal	
	Original	Modified	Original	Modified
Tool 1	3	3	0	3
Tool 2	3	3	0	3
Tool 3	3	3	0	3
Tool 4	3	3	0	3
Tool 5	3	3	0	3
Tool 6	3	3	3	3
Tool 7	3	3	3	3
Tool 8	0	3	0	3
Tool 9	3	3	0	3
Tool 10	3	3	0	3

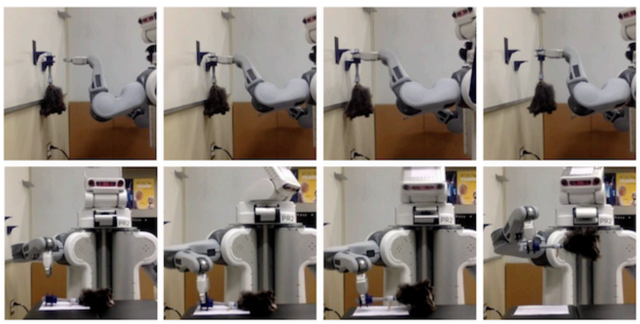

Fig. 7. Snapshots of the PR2 grasping a modified tool in the vertical and horizontal settings.

For original tools a high success rate was achieved in the *vertical* grasping tests. This was because the friction at the grasp points and gravitational forces were aligned in this setting, hence generating less torque disturbances on the grasped tool. In this setting, the robot had difficulty only with Tool 8 as a result of its asymmetric handle that did not allow a stable grasp with a parallel gripper.

In the *horizontal* tests, the success rate for grasping original tools was much lower. Although the robot could successfully close the gripper on the tool handle, in most cases it was unable to lift the tool up. The friction at the grasp point was not sufficient to counterbalance the torque generated by the tools' own weight. The only two tools that the robot was able to successfully grasp in this situation (Tools 6 and 7) were the ones with the smallest weight and length (*i.e.* shortest moment arm) (Table I).

Table IV presents the *stability* of grasping original and modified tools. In both vertical and horizontal tests the Griple resulted in 100% stable grasps. In contrast, none of the original tools were stable in the direction parallel to the grasping surface. Some grasps were stable in the direction normal to the grasping surface. These were mainly the shorter tools (Tools 2, 4, 6, 7, and 8) that had a smaller moment arm for forces applied near the tool's application surface. However, exceptions were also observed for shorter, original tools that had slippery texture (Tools 5, 9, and 10) or have limited contact areas on the handles (Tool 9). For longer tools (Tools 1 and 3) the external force applied during the test was sufficient to open the PR2's gripper. The Griple was successful in mitigating these issues in grasping the modified tools.

TABLE IV

NUMBER OF STABLE GRASPS IN EACH TEST OUT OF 3 TRIALS.

	Vertical				Horizontal			
	Original		Modified		Original		Modified	
	‖	⊥	‖	⊥	‖	⊥	‖	⊥
Tool 1	0	0	3	3	0	0	3	3
Tool 2	0	3	3	3	0	3	3	3
Tool 3	0	0	3	3	0	0	3	3
Tool 4	0	3	3	3	0	3	3	3
Tool 5	0	0	3	3	0	0	3	3
Tool 6	0	3	3	3	0	3	3	3
Tool 7	0	3	3	3	0	3	3	3
Tool 8	0	3	3	3	0	3	3	3
Tool 9	0	0	3	3	0	0	3	3
Tool 10	0	0	3	3	0	0	3	3

‖: Stability in the direction *parallel* to the grasping surface (*right*).
⊥*: Stability in the direction* normal *to grasping surface* (left).

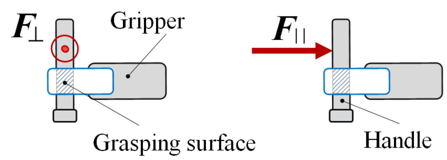

TABLE V

SUCCESS RATES DURING CLEANING TASKS

	Original tool	Modified tool
Tool 1	0.66	0.96
Tool 2	0.96	1.00
Tool 3	0.53	1.00
Tool 4	1.00	1.00
Tool 5	0.89	0.98
Tool 6	0.75	1.00
Tool 7	1.00	1.00
Tool 8	0.97	0.99
Tool 9	1.00	1.00
Tool 10	0.89	0.95

B. Experiment 2: Tool application

Table V presents the robot's *success* in cleaning the surface with each tool. Snapshots of the PR2 performing different cleaning tasks and before/after pictures of the cleaning surface are shown in Fig. 8). Overall, we observe a better cleaning performance when using tools with a Griple, particularly for longer tools (Tools 1 and 3). Original tools with short handles were also effective; however, this was partially due to the experimenter's assistance in handing the tool to provide the most stable possible grasp. In other words, if the tool was grasped by the robot itself and then applied, the cleaning performance would have been lower and in some cases not possible.

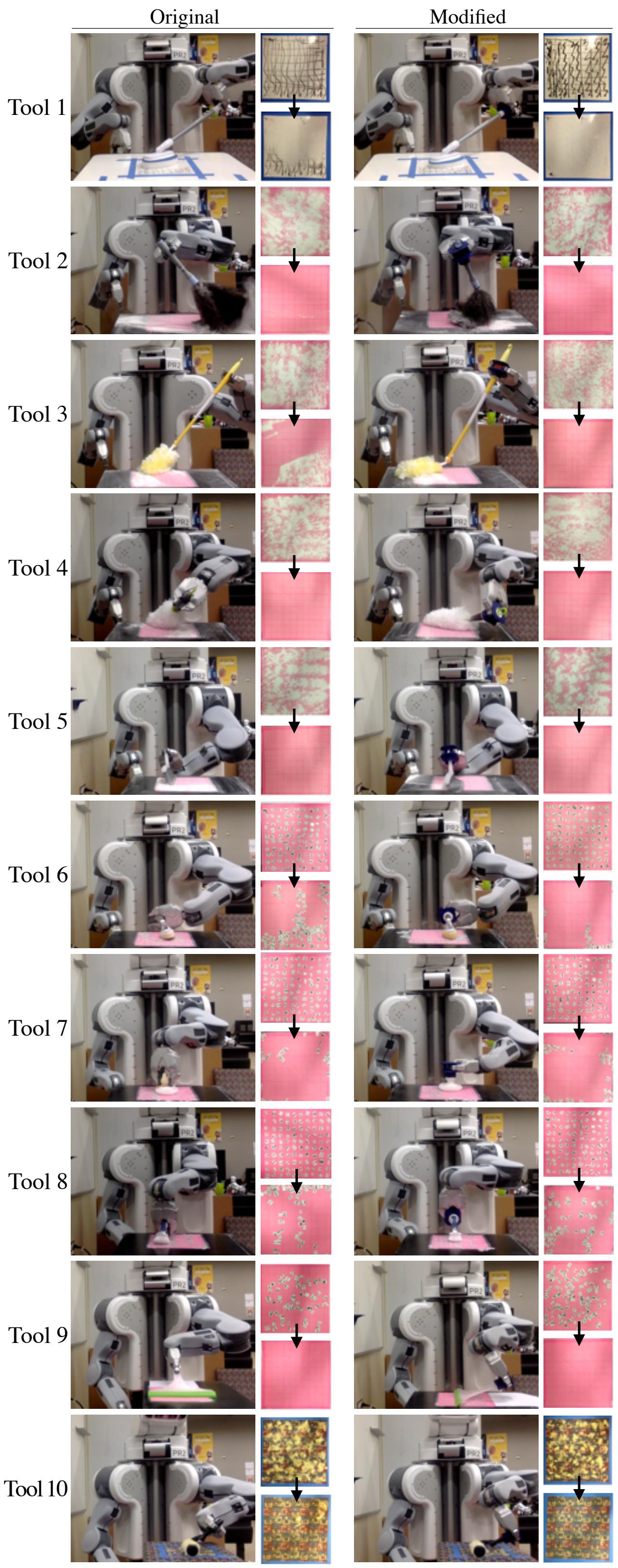

Fig. 8. Snapshots of the PR2 cleaning different surfaces with 10 cleaning tools and before/after pictures of the surface being cleaned with (left) original tools and (right) modified tools that have a Griple. See Table II for a description of the tests.

TABLE VI
NUMBER OF SUCCESSFUL PLACEMENT ACTIONS IN EACH TEST OUT OF 3 TRIALS.

	Vertical		Horizontal	
	Original	Modified	Original	Modified
	S P F	S P F	S P F	S P F
Tool 1	1 0 2	**3** 0 0	0 0 3	**3** 0 0
Tool 2	2 0 1	**3** 0 0	1 2 0	**3** 0 0
Tool 3	2 0 1	**3** 0 0	0 0 3	**3** 0 0
Tool 4	**3** 0 0	**3** 0 0	**3** 0 0	**3** 0 0
Tool 5	2 0 1	**3** 0 0	2 1 0	**3** 0 0
Tool 6	**3** 0 0	**3** 0 0	**3** 0 0	**3** 0 0
Tool 7	**3** 0 0	**3** 0 0	**3** 0 0	**3** 0 0
Tool 8	2 0 1	**3** 0 0	0 2 1	**3** 0 0
Tool 9	**3** 0 0	**3** 0 0	**3** 0 0	2 1 0
Tool 10	2 0 1	**3** 0 0	**3** 0 0	**3** 0 0

S: Success; P: Partial success; F: Failure

C. Experiment 3: Tool placement

Table VI presents the robot's *success* in placing the tool back in its initial configuration. Again we observe close to perfect placement of tools with a Griple. For original tools, placement onto a horizontal surface was more challenging than hanging the tool onto a jig. These were for the same reasons as the difficulties observed in Experiment 1. Failures with original tools were often caused by the tool rotating around the grasp point due to gravitational forces and, in some cases, slipping before being released.

VI. RELATED WORK

A. Robotic grasping, tool use and cleaning

A robot needs to be capable of autonomously grasping a tool before it can use it. All aspects of robotic grasping, from gripper design to perception and control, have been studied for decades [3]. Recent advances in perception and machine learning have allowed reliable grasping of unknown objects (*e.g.* [20], [5]). Available open source grasping software (such as GraspIt! [17] or Openrave [10]) can achieve unstructured grasping with low-cost sensors such as the Kinect sensor. While these approaches aim to address the general grasping challenge through sophisticated perception and grasp optimization methods, we believe that cost-effective and feasible modification to the environment can make the challenge much easier; hence achievable at rates that would be required for practical commercial robots.

Work in the area of robotic tools use has so far been sparse (*e.g.* [21], [12], [16]) partly due to the challenge of maintaining a stable grasp on everyday human tools. We believe that the Griple will open up new opportunities in this direction.

B. Gripper and end-effector design

Two alternative approaches for enabling robotic tool use are (i) designing specialized grippers and (ii) designing tool end effectors. Numerous efforts have been made to design multi-finger robotic hands that can mimic the human hands [2], however dexterous grasping and manipulation of human tools are still challenging. Innovative attempts have been made to design grippers that can adapt to a variety of objects with a wide range of shapes, sizes and weights. Under-actuated grippers/hands have demonstrated impressive grasping abilities [11], [13] with simple structure and reliable control. Alternative designs include jamming based grippers and low-cost end-effectors designed for non-prehensile grasping, both of which can pick up unknown objects without the need for any force feedback [6], [22]. These approaches have several trade-offs. For under-actuated hands/grippers it is challenging to preserve the precision when adopting elastic components. Novel grippers are often designed for lifting different objects/tools without consideration for performing further manipulation tasks with them.

In principle, our approach is most similar to work on custom end effector design and attachment/detachment mechanisms [15]; however, we aim for a much lower cost solution.

C. Structuring the environment for robots

Robots in automobile factories and warehouses demonstrate the potential for robustness in environment structured for the robot. Our approach is to induce similar structure in currently unstructured environments in which robots have the potential to perform useful tasks. One example of this approach from previous research in service robotics is work by Nguyen et al. [18] in which the robot benefits from structure in the environment provided for service dogs (*e.g.* tying red towels on drawers to make opening them easier).

VII. Limitations

The Griple is particularly designed for objects with handles. Many objects in home environments do not fall into this category. Nonetheless, many of these objects are better suited for PR2-like parallel grippers. Furthermore, the ability to use human tools alone will greatly expand the set of useful tasks that can be done by robots.

One concern with permanently modifying tools is that they might loose their usability for humans. While some placements of the Griple would mitigate this issue, a better solution would be to add a handle for human hands to the Griple design or make the Griple detachable.

Although we believe that the Griple will facilitate the *perception* of tools (localization and tool recognition), the experiments presented in this paper did not address this point. By placing the tools in the same configurations during grasping experiments, we made the assumption that the tools could be accurately localized in both conditions.

VIII. Conclusion

We believe that reliable manipulation in human environments can be achieved by making certain objects more robot-friendly; particularly objects that will be used exclusively by robots (*e.g.* cleaning tools). In this paper we present the design of a tool attachment, called Griple, that makes human cleaning tools more robot friendly. Through a series of experiments we demonstrate the performance gain provided by the Griple on 10 different cleaning tools in grasping, applying, and placing cleaning tools.

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