

# Physical Simulation with Force Feedback Aids Robot Factors Design

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**Abstract**—“Robot factors” design, analogous to ergonomics for humans, seeks to create devices and equipment that can be readily operated by robots, by considering typical capabilities of current robots throughout the design process. While a number of principles and heuristics for robot factors design have been identified, the successful design of hardware operable by autonomous robots often depends in practice on the designer’s intuition about robot capabilities, developed through personal experience working with robots. Here we present a tool we have developed to help evaluate a potential device design for usability by a robot, by allowing a designer to in effect teleoperate a virtual robot and attempt the operation of the device. The tool uses a 3D physics-based simulation built in Unity, and a Phantom Omni / Geomagic Touch haptic device that controls the virtual robot’s end-effector and provides force feedback. Through user studies, we show that the use of this tool can significantly improve a user’s estimation of the suitability of a design for robot operation, in two case studies involving replacing a unit in a modular hardware system and unzipping a canvas bag. By incorporating the use of such a tool early in the design cycle, designers can more effectively develop equipment to be used by autonomous robots without themselves needing direct robotics experience; as a result, robots will be able to take on more tasks in the nearer term with current robot technology.

## I. INTRODUCTION

While most work in robotics research focuses on increasing the capabilities of robots to approach those of humans, “robot factors” [1]–[4] takes a complementary approach: By designing a task with current robot capabilities in mind, it can be brought within the reach of current autonomous robots [5]. As a result, such tasks can be given over to robots on a much shorter time scale than if robots are required to operate equipment designed solely for humans. Moreover, tasks and equipment designed with robot limitations in mind can also benefit human users, making operation easier (eliminating the need for dexterous manipulations, bimanual operation, large forces, etc.) and increasing the range of users and conditions for which the task can be successfully performed.

Human factors design (ergonomics) is very extensively studied and its principles are well understood by many

designers, who additionally have deep intuition for human capabilities through their experience being humans [6]. By contrast, designers’ intuition for what is easy or hard for current robots can often be markedly poor. Experience working with robots is an effective way to develop such intuition, but that experience is available only to a small subset of designers. A tool to help stand in for that intuition could therefore improve usability for robots widely, and accelerate the timeframe for robots to provide effective help in many human domains.

Here we present a tool intended to let a user test a potential design for robot usability early in the design cycle. The tool provides a virtual environment in which the user can teleoperate a simulated robot and attempt to use it to operate the design as envisioned. The interface uses an off-the-shelf device with a stylus that provides direct 6DOF control for the pose of the end-effector, with force feedback to alert the operator to collision states and keep them from pushing through. The premise is that anything difficult for a human operator will be more difficult for an autonomous robot, with its more limited perception, etc. Thus difficulties the user encounters can be identified as likely sticking points for a robot, and the design modified accordingly. By addressing such issues early on (before physical prototyping, extensive additional design effort, etc.), the system development process can be made quicker and more efficient.

We first describe the tool and envisioned workflow (§II), and then present user studies we conducted to evaluate its utility. §III describes two example tasks, and two candidate designs for each, that we used in these studies. §IV describes the results of user tests. Our study subjects were professional design engineers at Collins Aerospace as well as Harvard engineering and design students. The results showed that users of our tool had significantly better ability to assess the difficulty of designs not suited for robot use, with greater confidence and lower variance in their evaluations, and to discriminate the difficulty of human-centered vs. robot-centered designs, compared to having access to CAD alone.

## II. HAPTIC DESIGN TOOL

The tool provides a simulated 3D environment in which a user can load a device design of interest, and play the role of a robot attempting to operate it (Fig. 1). The user controls the simulated robot using a Phantom Omni / Geomagic Touch haptic device: the position and orientation of the stylus directly sets the pose of the simulated end-effector; pressing and releasing a button on the stylus closes and opens the simulated gripper; the position of the physical stylus is

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Fig. 1. A user interacting with our haptic design tool. A Phantom Omni / Geomagic Touch haptic device directly controls the pose and actuation of a simulated parallel-jaw gripper. The device provides force feedback reflecting collisions in a physics-based simulation. By playing the role of a robot attempting to operate some item of equipment in simulation, the user can better evaluate what the physical usability of that equipment would be for a robot, and identify points of particular difficulty. Incorporating such a tool into the design cycle can thereby facilitate designing equipment operable by autonomous robots, without requiring accurate intuition built on extensive robot experience.

constrained by force feedback based on collisions of the simulated gripper or an object it holds with other objects in the virtual environment; and the effective inertia of the physical stylus varies according to the mass of an object held by the simulated gripper. The software is built in Unity, and uses its physics engine. The user can move the camera within the virtual environment using keyboard and mouse.

The simulation environment includes only the end-effector rather than a complete robot. This choice lets the user focus on the interactions the robot would have with the equipment design being tested, without needing to be concerned with the motion of the rest of the robot, self-collisions, etc. We assumed a single arm/manipulator, as the most common hardware configuration for single robots.

The tool's place in the design cycle would follow the initial CAD design of a device, component, or system, allowing a designer to get a clearer sense early on of potential difficulties that an autonomous robot might have in operating it. They would then have the opportunity to go back and revise the design when the revision cost is lower, without needing to progress to a stage of physical fabrication, or without the

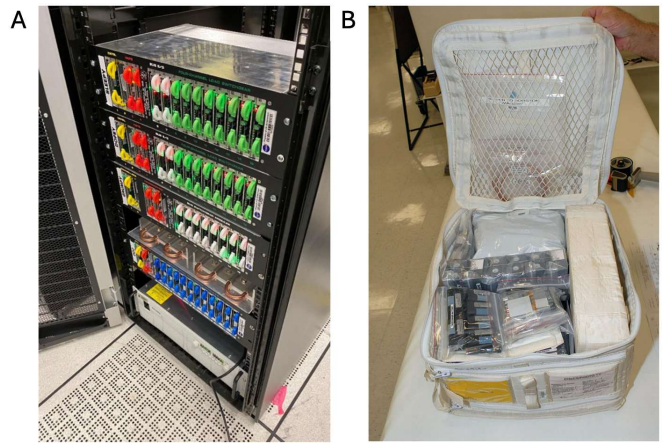


Fig. 2. Two examples of equipment whose operation by autonomous robots would aid NASA missions. (A) A rack of power modules from NASA's Advanced Modular Power Systems (AMPS) project [7]. Replacing a module involves several steps of manipulating small levers in confined spaces (Fig. 3A). (B) A canvas cargo transfer bag (CTB). CTBs are extensively used for equipment storage on the International Space Station, and their use and inventory management consumes significant astronaut time. Opening a CTB involves manipulating a small zipper pull tab along the edge of a container that may be deformable and/or light (Fig. 4A).

system design progressing such that dependencies of later system elements on problematic features become entrenched.

The workflow thus requires converting a device design from CAD software to a format that can be imported into Unity. This operation can be nontrivial, depending on the details of mechanisms within the device design. A software tool we developed to aid with this conversion, while adding minimal overhead for the user, is available at <https://github.com/nathanmelenbrink/Fusion2PyBullet>.

### III. USER STUDIES

To quantitatively evaluate the utility of the haptic tool, we conducted a user study in which participants were asked to estimate the difficulty that a given hardware design would pose for an autonomous robot attempting to use it.

In the typical workflow for use of the tool as envisioned, a user would first create a design for a device or system using commonly available tools like standard CAD software, and then use the haptic tool to help better estimate usability for a robot and identify issues calling for design revision. Asking a participant to create new designs of any complexity from scratch would not fit easily within the constraints of a user study session; therefore for each task, we provided participants with a pre-designed system and a written description of how it should be operated.

#### A. Tasks and designs for evaluation

We considered two example tasks that a robot may be called on to perform (Fig. 2):

- Task 1) *Replace a unit in a modular system*: unfasten the original unit, remove it, insert a new unit, fasten it in place.
- Task 2) *Open a canvas bag*: unzip the lid of a cuboidal bag made of a soft (deformable) material, open the lid.

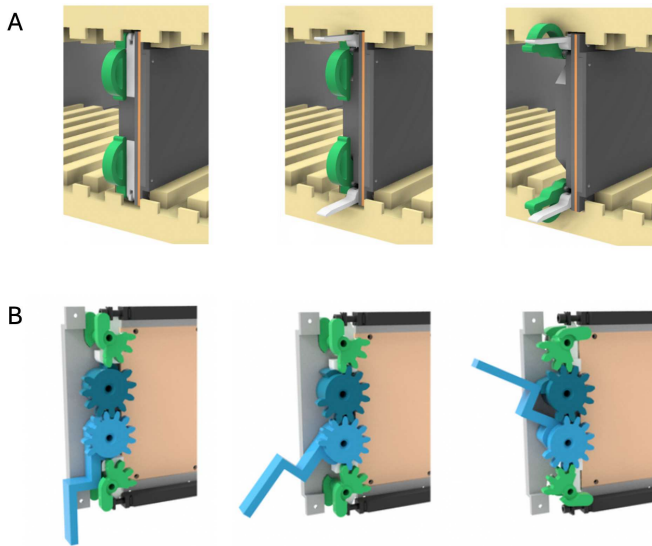


Fig. 3. Interfaces for Task 1, replacing a unit in a modular system. (A) Design 1a: In the original design intended for human operation, removing a module requires manipulating four small levers—two wedgelocks (gray) followed by two injector handles (green)—before sliding the module out of its chassis [7]. (B) Design 1b: In our redesign intended for robot operation, those manipulations are replaced by a single large lever (light blue), which drives a gear assembly that performs the multiple functions [5]. (Images adapted from [5]; ©2022 IEEE.)

These tasks were chosen based on discussions with NASA personnel regarding desired autonomous operations. The first is an operation characteristic of a number of different specific cases, e.g., in the context of a modular power system [7] or a water filter in a life support unit [8], where modular units need replacing as a matter of regular operation or routine maintenance. The second is based on the Cargo Transfer Bags (CTBs) used for transporting and storing equipment. The ability to pass these tasks to autonomous robots would free astronauts from time-consuming or tedious operations, and increase autonomy and resilience for space habitats during uncrewed periods [9].

We chose two possible designs for each system—one based on the current implementation designed for human operation, one based on our redesign for use by autonomous robots (Figs. 3, 4):

Design 1a) *Human-centered module*: raise two small levers (wedgelocks) to unlock unit, raise two other small levers (injector handles) to eject unit, slide unit out, slide new unit in, lower injector handles, lower wedgelocks.

Design 1b) *Robot-centered module*: raise a large lever to both unlock and eject unit, slide unit out, slide new unit in, lower lever.

Design 1a was based on the hardware developed for NASA’s Advanced Modular Power Systems (AMPS) project [7].<sup>1</sup> Key

<sup>1</sup>In the actual design, an additional requirement was that both wedgelock levers must be moved simultaneously, and likewise for the injectors—intrinsically bimanual operations. We removed this simultaneity requirement in the version of the task given to study participants, since they would be asked to evaluate the design’s usability by a one-armed robot.

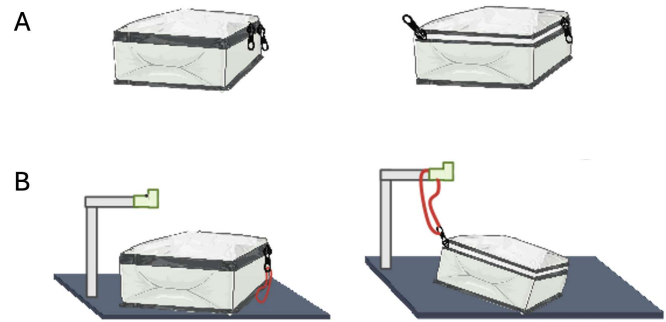


Fig. 4. Interfaces for Task 2, opening a canvas bag. (A) Design 2a: With a standard setup intended for human operation, unzipping the bag requires gripping a small zipper pull tab and guiding it around the edge of the lid, typically while holding the bag in place with the other hand and pulling against that resistance. (B) Design 2b: In our redesign intended for robot operation, a ring looped through the zipper pull tab (red) provides a larger target for grasping, the ring is put over a stationary hook (green), and the robot grips the bag directly and pulls against the resistance of the hook to guide the zipper around the lid.

difficulties for an autonomous robot include getting a typical gripper into the constrained space to lift either lever type. Design 1b replaces both sets of small levers by a single large lever activating a gear assembly that coordinates the multiple motions. This design, first presented in our previous work [5], allows this task to be performed by an autonomous robot with one arm and a two-finger gripper (Fig. 5).

Design 2a) *Human-centered bag*: grasp the zipper pull tab, pull it around the edge of the lid, grasp and raise the lid.

Design 2b) *Robot-centered bag*: grasp a large ring looped through the zipper pull tab, put the ring over a hook attached to a wall, grasp the bag on the opposite side from the zipper, pull against the resistance from the hook, reposition bag and grasp for each corner, grasp and raise the lid.

Key difficulties for an autonomous robot using Design 2a include grasping the small, lightweight zipper pull tab, and holding the bag in place while pulling the tab. Design 2b addresses these issues with the addition of two simple low-mass elements (ring and hook). This design allows this task to be performed by an autonomous robot with one arm and a two-finger gripper (Fig. 6), and has not previously been presented.

## B. Study design

We designed a mixed study to evaluate the following questions:

- Q1) How does access to the haptic tool affect a designer’s estimation of the difficulty a design would pose for an autonomous robot? In particular, does access to the tool improve the ability to recognize high difficulty for designs that are really not suited for robot operation, and operations of particular difficulty?
- Q2) How does access to the haptic tool affect a designer’s confidence in such estimations?

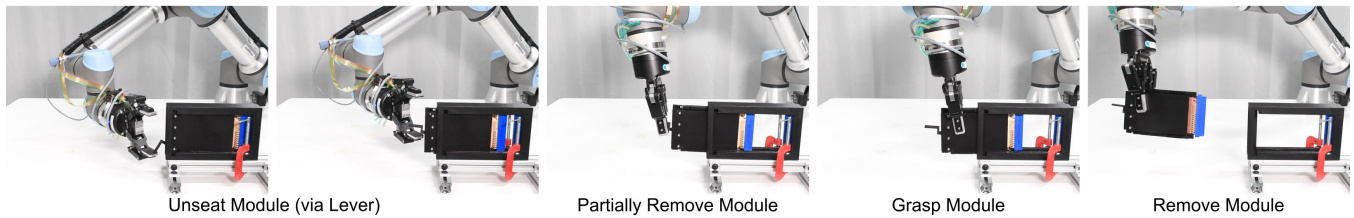


Fig. 5. The robot-centered Design 1b allows a robot arm with a parallel-jaw gripper to autonomously perform Task 1, replacing a modular unit. (Images adapted from [5]; ©2022 IEEE.)

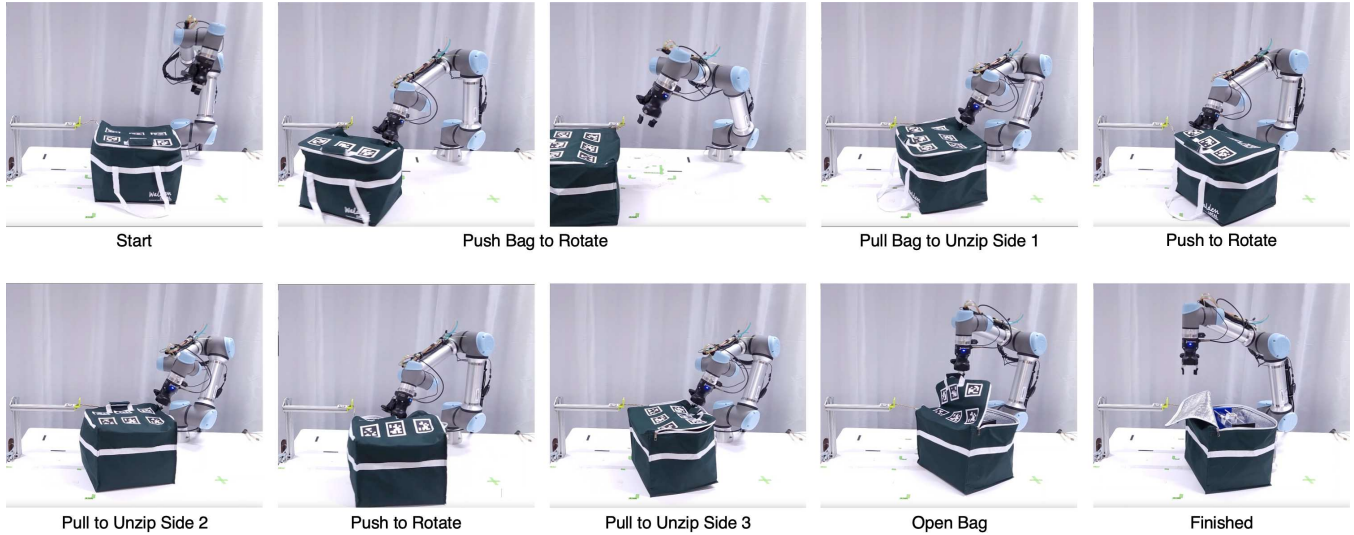


Fig. 6. The robot-centered Design 2b allows a robot arm with a parallel-jaw gripper to autonomously perform Task 2, opening a canvas bag. AprilTags [10] on the lid allow the robot to estimate the bag's pose, using a wrist-mounted camera, to plan grasps.

- Q3) Does even brief access to the tool affect a user's continuing ability to make better estimations?
- Q4) Do users with less experience with robots gain more benefit from the tool?

Each study participant was given one design for each task, and asked to estimate the difficulty it would pose for a robot with one arm and a two-fingered gripper (a photo of a Fetch Mobile Manipulator platform was provided as an example). The design (human- or robot-centered) and the order of tasks were randomly chosen. There were thus 8 experimental conditions in total: {Design 1a vs. 1b}, {Design 2a vs. 2b}, and {Task 1 vs. 2 presented first}.

The participant rated each design first after examining it with a CAD interface (Autodesk Fusion 360), and then again after interacting with it using the haptic tool (a within-subjects part of the study). The CAD environment contained an instance of the gripper that would be used, along with the design, to provide information about their relative sizes. Since the normal workflow for the haptic tool would involve first creating a design in CAD and then testing it out with the tool, participants were always given the CAD condition before the tool condition. After evaluating the first design using CAD and before examining it with the haptic tool, participants practiced using the tool in a sample environment and task involving placing rings on pegs, to grow accustomed

to its use. Since seeing both the human- and robot-centered designs for a single task would likely bias evaluation for whichever was presented second, each participant was assigned only one design for each task (a between-subjects part of the study). Participants were given as much time as they wanted to examine each design both in CAD and using the haptic tool.

After examining a design with either interface, participants were asked to estimate its difficulty for the robot, and their confidence in that rating, both on a 7-point Likert scale. They also specified which steps of the task they thought would be easiest and hardest for the robot; and they provided free responses regarding rationale for their choice of difficulty rating, and other comments about the task and design. After the evaluation with the haptic tool, they were also asked for a free response as to whether it provided insights or information not available with the CAD interface. At the end of the session, there was an opportunity for free response regarding any other thoughts about the tool or procedure.

Our subjects comprised 15 members of the Mechanical Design Engineering group in the Space Systems Hardware Engineering Department at Collins Aerospace, and 5 participants from Harvard's schools of engineering and design. The latter participants received a \$20 gift card as compensation for their time.

Prospective study participants were asked to complete a pre-survey in which they self-rated their prior experience with both CAD software and robots, on a Likert scale from 1 to 5.

## IV. RESULTS

### A. Quantitative

**Use of the haptic tool increases recognition of difficult designs (Q1).** Difficulty rating for the human-centered designs significantly increased after use of the tool ( $3.9 \pm 1.8$  to  $6.5 \pm 0.5$  for Design 1a,  $p = 0.0051$ ;  $3.4 \pm 1.6$  to  $6.4 \pm 0.8$  for Design 2a,  $p = 10^{-4}$ ). No significant change was observed for the robot-centered designs ( $3.6 \pm 1.2$  to  $3.9 \pm 1.6$  for Design 1b,  $p = 0.49$ ;  $4.1 \pm 1.3$  to  $4.5 \pm 1.4$  for Design 2b,  $p = 0.51$ ). Reported  $p$ -values are based on two-tailed paired T-tests.

**Use of the tool can increase accuracy in evaluation of difficulty (Q1).** A narrower distribution in ratings across study participants can be interpreted as a better ability to estimate the “true” difficulty of a task. Variance in ratings decreased after use of the tool for Design 1a ( $p = 0.0047$ ), although the effect did not reach significance for Design 2a ( $p = 0.059$ ). No significant decrease was observed for the robot-centered designs ( $p = 0.29$  for Design 1b;  $p = 0.88$  for Design 2b). Reported  $p$ -values are based on two-tailed F-tests.

**Use of the tool improves resolution of discrimination between designs (Q1).** Based on examining the designs in CAD only, participants did not rate the human-centered designs as being of significantly different difficulty than the robot-centered designs ( $p = 0.66$  for Task 1;  $p = 0.30$  for Task 2). After examining the designs using the haptic tool, the ratings for human-centered and robot-centered designs were significantly different ( $p = 0.00041$  for Task 1;  $p = 0.0014$  for Task 2). Reported  $p$ -values are based on two-tailed two-sample equal-variance T-tests; results do not change appreciably when using unequal-variance tests.

**Use of the tool provides meaningful new information about executing a task (Q1).** In 22 of the 40 total cases, the participant’s expectations about which steps of a task would be easiest and hardest changed after use of the tool. In 14 of the cases, one or more steps that had initially been thought would be easiest were revised to be considered hardest, and/or vice versa. In 4 cases, the steps predicted to be easiest and hardest were completely reversed after use of the tool.

**Use of the tool can increase confidence in evaluation of difficulty (Q2).** Confidence for ratings for Task 1 significantly increased after use of the tool ( $4.1 \pm 1.6$  to  $5.4 \pm 1.2$  for Design 1a,  $p = 0.019$ ;  $3.9 \pm 1.2$  to  $5.2 \pm 0.8$  for Design 1b,  $p = 0.00092$ ). No significant change was observed for Task 2 ( $5.0 \pm 1.6$  to  $5.9 \pm 1.3$  for Design 2a,  $p = 0.018$ ;  $4.2 \pm 0.9$  to  $4.8 \pm 0.9$  for Design 2b,  $p = 0.14$ ). Reported  $p$ -values are based on two-tailed paired T-tests.

**No evidence was found for user intuition improving after brief access to the tool (Q3).** We had hypothesized

that after using the tool in the first task presented to them—actively teleoperating a virtual robot and considering task difficulty for it—that experience might have a lingering effect that would improve a participant’s ability to make further such evaluations, at least in the immediate term. (Consistent with this hypothesis, three study participants wrote that their rating of the second design using CAD was “based on” their experience with the first design using the haptic tool.) If so, we would expect that for any given design, the change in rating before and after use of the tool would be smaller if that task was the second one presented to the participant, compared to if it was the first presented. However, our data showed no significant difference in that change for any design ( $p > 0.15$  for all four designs, using two-tailed two-sample T-tests, whether equal or unequal variance is assumed).

**No evidence was found for the tool providing greater benefit for users with less robot experience (Q4).** We had hypothesized that users who had more direct experience with robots (and their characteristic limitations) would be better able to estimate task difficulty, without use of the tool. This better estimation might be reflected in a smaller change in rating before and after use of the tool, or a higher initial rating for the human-centered designs (reflecting the user’s ability to recognize the difficulty for a robot without needing to try it out). However, no correlations between self-reported robot experience and either of those measures reached statistical significance ( $p > 0.12$  in all cases).

### B. Qualitative

Participants reported that the haptic tool was helpful in providing key information more clearly and/or intuitively than the CAD environment. For instance, five out of eight participants evaluating Design 1a wrote that the haptic tool led them to recognize the size disparity between the interface levers and the gripper. (“*The robot seems much larger and clumsier. It is frustrating trying to maneuver it, and you realize things about the design that you wouldn’t have noticed otherwise. It is very similar with lessons learned from machining & assembling space hardware designs.*”) Eight out of ten participants evaluating Design 2a wrote about how the haptic tool let them recognize the issue of the bag moving, a factor they had neglected to think of in the CAD environment alone. (“*I didn’t think at first about the weight (or lack thereof) of the bag, I was mostly looking at the path of the zipper, the surface area, and thinking about the robot’s dexterity.*”)

Some participants reported that the haptic tool allowed them to discover alternate ways for a robot to approach the tasks that had not otherwise occurred to them. (“*The tool inspired me to try a few techniques I had not considered in the CAD program (1) getting one of the gripper fingers under the wedgelock (2) closing the gripper and then trying to open the wedgelock with the closed tool*”; “*Using the tool, I found it was more reliable to grip the bag, then attach the ring by manipulating the bag.*”)

Several participants commented on issues with the haptic tool in its current form. 12 of the 20 participants wrote about having difficulty performing the task due to camera issues, limiting their ability to see the area where the gripper interacted with the device. Five participants wrote about encountering unrealistic physics in the simulator, with objects passing through one another, instability, etc. Two commented on the limitations to the force feedback: the haptic device we used drives the position of its stylus but not its orientation, and when the user presses the stylus button to close the gripper, there is no separate tactile signal to indicate whether the gripper has closed on an object or on empty air.

## V. DISCUSSION

The user studies show that testing out a device design in simulation, using a 3D stylus with force feedback to teleoperate a virtual robot, can significantly improve one's estimation of the usability of a design for a robot (with its concomitant physical limitations). The tool provides insights that may not be apparent through traditional design evaluation methods as provided in a CAD interface. The effect holds even for users with substantial previous experience with robots. Incorporating such a tool into the design cycle could therefore speed the development and effectiveness of devices and systems intended to be operable by autonomous robots.

Because the tool is based on the user teleoperating a robot, it highlights *physical* points of difficulty that might be encountered by an autonomous robot, but not necessarily control issues where the robot might have difficulty autonomously executing an action for other reasons. In future work, a complementary tool could be used to identify “cognitive” points of difficulty, by having a virtual robot attempt to operate a candidate device design with full autonomy within a physics-based simulation. The simulation part of the system presented here, and the software to aid the conversion from CAD to Unity-readable format, could provide a basis on which to build such a tool. Similarly, a future extension could be used to develop or train controllers for autonomous use of candidate devices, as a goal in itself.

Improvements to the system in the short term may include interface modifications, like additional camera control options or translucency of the rendered gripper, to address the viewing issues identified by the study participants. The conversion software tool will also continue to be improved to further streamline the export/import step between the CAD and Unity environments. Resolving the physics glitches in the simulator would also be a significant improvement, although real-time complex collisions notoriously pose challenges for typical physics engines [11]–[13]; the results of our user study also show that the tool has significant value even when these glitches are present, with users instructed that the simulation is meant to provide intuition rather than perfect physical fidelity.

In the longer term, the hardware element of the tool could be expanded to improve the user's experience and accommodate additional use cases. A second haptic device

could be integrated to permit evaluating operation of a candidate device by a two-armed robot. Additional degrees of force feedback, as requested by some study participants, could be provided, for instance through the combination of multiple simpler devices [14]. Adding tools like a VR headset, or more actively incorporating other lessons from teleoperation studies [15], could also improve the user's ability to teleoperate the virtual robot, ensuring that problems they encounter are due to the device design and not to interface issues.

In summary, by allowing designers to interactively assess the feasibility of their designs for robot operation, the tool provides insights on how a robot would interact with the design, that are difficult to obtain through CAD alone, providing a tool to improve designing hardware made for robotic manipulation. Our study shows that the tool enhances both the accuracy and confidence of design evaluations, which could facilitate the design process in the future. As robots increasingly enter human spaces and take on more tasks traditionally performed by humans, tools like this will help in ensuring that system designs are not only functional but also suited for robot use.

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