Sharp-edge Handheld Identifier and Remover in Low-gravity Extravehicular Environments

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One of the most significant problems astronauts face during Extravehicular Activities (EVAs) is the hazard posed by sharp edges on the International Space Station (ISS) handrails created by space debris. Tears in EVA gloves due to sharp edges risk suit depressurization and astronaut injury, and may warrant an early termination of the EVA altogether. The current method for detecting and removing these sharp edges is inadequate as it relies primarily on visual cues and renders affected handrails unusable. In this paper, we present the design of SHIRLEE, a Sharp-edge Handheld Identifier and Remover in Low-gravity Extravehicular Environments. SHIRLEE is an entirely mechanical device for detecting and removing sharp edges specifically tailored to EVA handrails. Using customized detection bars that snap outward when caught on a sharp edge, SHIRLEE reshapes the hazardous edge with a ceramic steel smoothing stone. Results from testing in a microgravity environment at the Neutral Buoyancy Laboratory (NBL) validated the effectiveness of SHIRLEE's detection and removal methods. In addition, during testing, NASA divers praised SHIRLEE's ergonomic design, simplicity, and modularity. These qualities make this tool advantageous over the current methods used for sharp-edge detection and removal.

I. Introduction and Assessment of Current Practice

Astronauts aboard the International Space Station (ISS) rely on handrails located on the outside of the ISS to move around during Extravehicular Activities (EVAs.) However, due to their location, the handrails are regularly exposed to Micrometeoroids and Orbital Debris (MMOD) which can create small sharp edges on the handrail surface upon collision [1]. These edges pose a serious threat to astronaut safety, as they can damage astronaut EVA gloves, risking suit depressurization and astronaut injury. NASA Hypervelocity testing suggests that MMOD craters are considered one of the leading possible causes of glove damage during EVAs [1]. MMOD craters are suspected to have contributed to EVA glove damage reported during Space Shuttle missions such as STS-109, STS-110, STS-116, STS-118, STS-120, and STS-125. In two of these cases, glove damage caused early termination of a spacewalk [1].

Current solutions to mitigate the risk of sharp-edge damage to EVA gloves involve (1) recording the handrails on which sharp edges have been visually detected and having astronauts avoid these handrails entirely during EVAs, and (2) temporarily clamping off large sharp edges to avoid accidental contact [1]. Solution 1 utilizes the ISS Imagery Inspection Management System (IIMS), which contains over 200 recorded areas of MMOD impact on handrails and serves as a functional database of potential sharp edges on handrails with photographs of any observed sharp edges. Solution 2 involves clamp tools, which are used to cover particularly hazardous handrail regions to prevent inadvertent contact. However, because this solution involves covering rather than removing, these clamps also make the majority of the handrail inaccessible to the astronaut. Thus, while these solutions have greatly reduced cut-glove incidents [1], such methods are not viable long-term solutions since they leave large portions of ISS handrails unusable, and do not methodically detect sharp edges.

An important consideration is that the above methods, outlined in Fig. 1, only address visible sharp edges. Ground testing by NASA/JSC Hypervelocity Technology Facility determined that crater lips of height 0.25 mm (0.01 inch) are sufficient to cut EVA gloves [1]. Thus, reliance on visual detection puts astronauts at serious risk of cutting their gloves on edges that are difficult to observe with the naked eye.

Our goal was to design a sharp-edge detection and removal device to eliminate the risk of sharp edges on the handrails by first detecting the specific location of the sharp edge along the handrail and then removing the edge without introducing new safety hazards [2]. A key component of our approach was to develop a localized removal process that targets specific areas on the handrail triggered by the detection process. Additional considerations include ease of use

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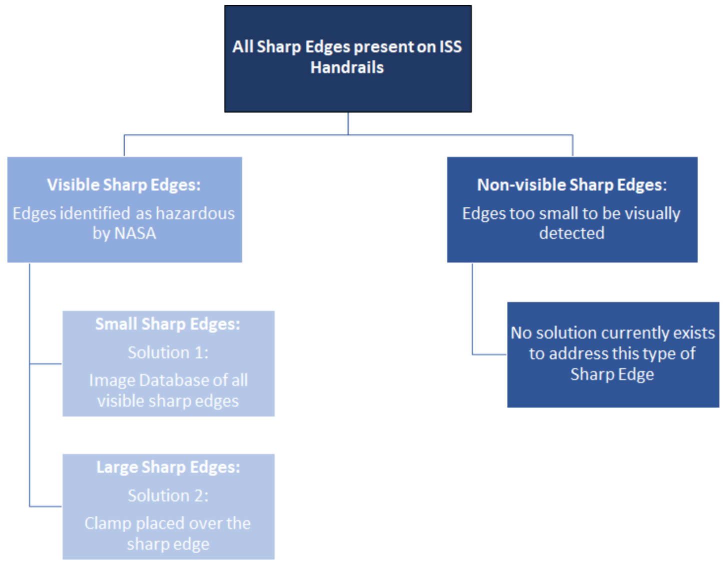

Fig. 1 A breakdown of sharp-edge hazards and current solutions

while in a pressurized spacesuit, specifically while wearing restrictive EVA gloves, functionality underwater for testing in the Neutral Buoyancy Laboratory (NBL), and adherence to general safety standards for tools used aboard the ISS.

Thus, we propose the Sharp-edge Handheld Identifier and Remover in Low-gravity Extravehicular Environments (SHIRLEE), a new and localized solution for sharp-edge detection and removal to eliminate the risk of sharp edges on ISS handrails while enabling astronauts to use the full handrail surfaces during their EVAs. SHIRLEE is a fully mechanical, 3D printed tool that detects sharp edges via a double-sided detection mechanism and removes them with a ceramic steel smoothing stone. SHIRLEE's detection mechanism features two bars that fit to the two different concavities of the ISS handrails and glide along the handrail surface until caught on a sharp edge. Once caught, the detection bar rotates ninety degrees outward to signal a detection of a sharp edge and reveals the inner removal mechanism. Removal entails rubbing a ceramic steel smoothing stone [3] on the handrail to reshape the sharp edge into a blunt protrusion. These blunt protrusions pose no risk to the astronaut and no longer activate the detection mechanism. The smoothing stone was inspired by the use of ceramic steel in ice hockey, where "skate stones" are used to reshape burred metal hockey blades without abrasing or damaging the skate blade itself. SHIRLEE also features water drainage holes for testing in the NBL, clear labelling of potential finger entrapment points, and reproducible components that can be replaced as needed.

II. Proposed Design

The final design, shown in Fig. 2, addresses both detection and removal of sharp edges. The two detection bars protruding from SHIRLEE are shaped to fit two different curvatures of the handrail faces. When run along a handrail, the detection bar catches on sharp edges and rotates outward, visually notifying the astronaut of the sharp edge. Beneath each detection bar is a smoothing stone, which can be accessed once the detection bar has rotated outward. The smoothing stone is a small block of ceramic steel that reshapes sharp edges in the same way that a hockey skate stone smooths down burrs on ice skate blades. Thus, after detecting a sharp edge with the detection bar, the smoothing stone can be rubbed against the sharp edge, smoothing down and removing the hazard without creating debris.

The assembled device is $9.75 \times 4.75 \times 3.50$ centimeters and weighs 195 grams. Every component other than the smoothing stone was 3D printed with PLA plastic and the cost of materials was under \$30. The manufactured device was glued together with an adhesive and includes vinyl stickers for hazard labeling and decoration.

A. Device Body

The body of the device (see Fig. 3 and Fig. 4) is 3D printed and includes drainage holes and a tether point. On each end of the body, there are two holes where the detection bars connect to the device. These holes each have four notches

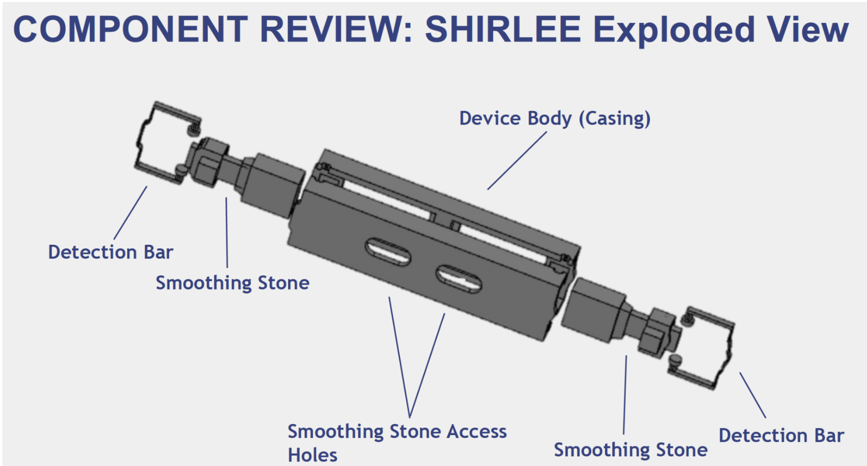

Fig. 2 Final Design

that allow the detection bars to snap in ninety degree rotations when a sharp edge is encountered. Additionally, the inner side of the body includes indented squares, which is where the smoothing stone casings snap into place.

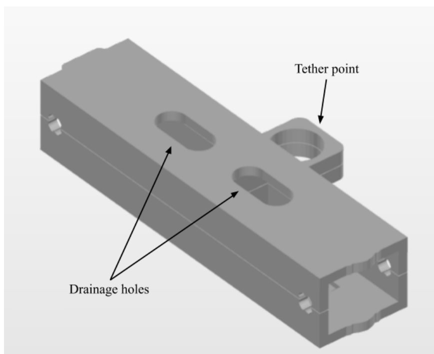

Fig. 3 The device body

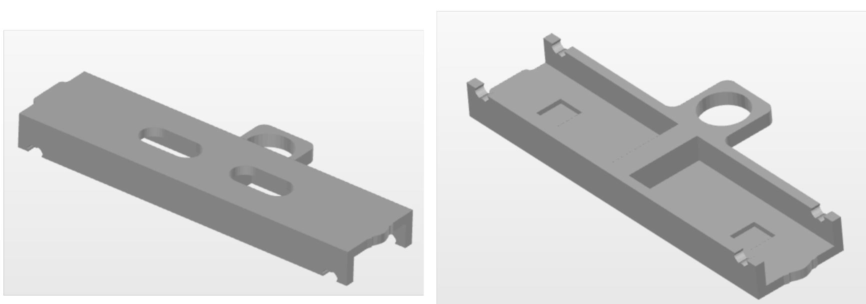

Fig. 4 Outer view (left) and inner view (right) of the device body

B. Detection Bars

The two detection bars, shown in Fig. 6, that protrude from the device are shaped to fit the two faces of the handrail (see Fig. 5), one flat and one curved, and are color coded. The detection bars fit into the rotation holes in the device body.

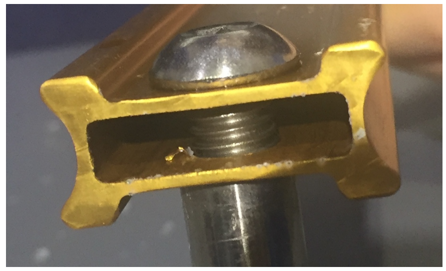

Fig. 5 A handrail: the flat face is on the top and the two curved faces are on the left and right

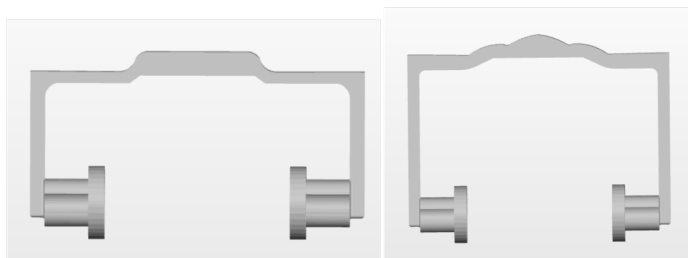

Fig. 6 The flat (left) and curved (right) detection bars

C. Smoothing Stone Casing

Beneath each detection bar is a smoothing stone protruding about half an inch from the device. Each smoothing stone is held in place by a smoothing stone casing (see Fig. 7). The top and bottom of the casings have extruded squares which snap into the body of the device.

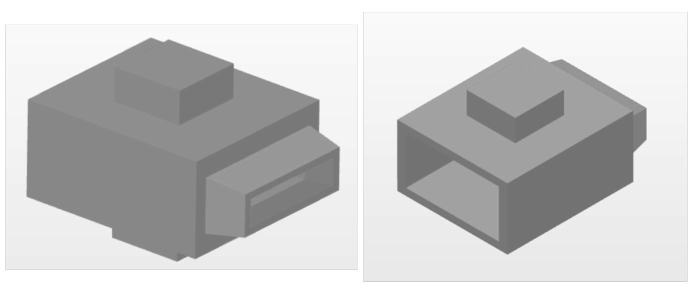

Fig. 7 Two views of the smoothing stone casing, which hold the smoothing stone in place

D. Smoothing Stone

The smoothing stones, made of ceramic steel, are used to remove the sharp edges. They are held in the smoothing stone casings and are behind the detection bars, protruding from the device. For ease of production, SHIRLEE is built to accommodate a 6" × 3" × 1" stone (see Fig. 8), which can be purchased directly from skate stone manufacturers in standard 280 grit.

Fig. 8 A ceramic steel smoothing stone

E. Assembled Device

When assembled, these parts form a completed device. The completed device is shown in Fig. 9 and the assembled prototype is shown in Fig. 10.

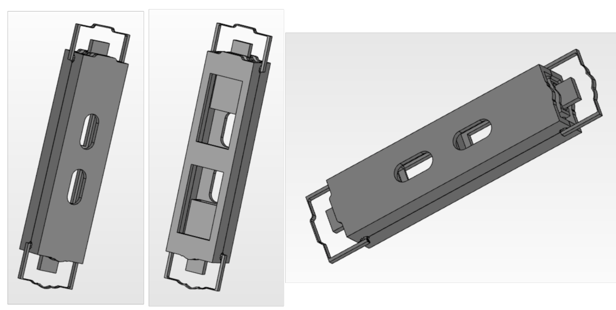

Fig. 9 The complete design

Fig. 10 The manufactured prototype

F. Safety

Safety was the chief consideration in the design of every component of the device. As such, many aspects of the design ensure user safety. First, the device is solely mechanical and has no electronic or pneumatic components. Additionally, operation of the device involves minimal contact with the device and no contact with pinch points where the detection bars connect to the device body. The pinch points are also clearly labeled with red vinyl decals. All corners and edges of the device are smooth, so there is no risk of damaging astronaut gloves. Lastly, the device includes drainage holes, which ensures the free flow of air and water when testing in an underwater environment such as the NBL. After being evaluated by the NBL safety review board and the NBL Dive Team, SHIRLEE was certified as meeting the NBL safety standards for EVA tools.

G. Device Operation

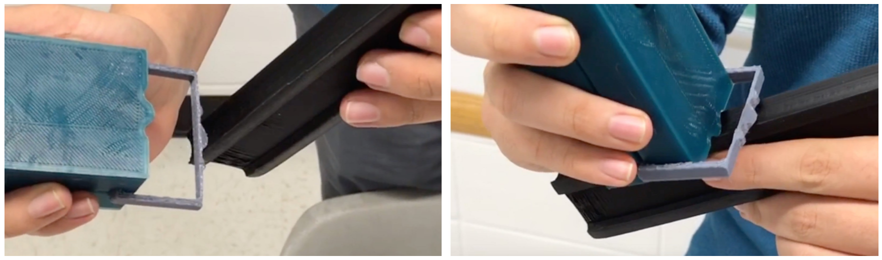

Fig. 11 A prototype in detecting (left) and removing (right) positions on a plastic, sample handrail

SHIRLEE can be held and operated with one hand, though using two hands or alternating between hands can make operation easier. To operate, the user should first attach a tether onto the tether point of the device to enable recovery if necessary. The outer casing of SHIRLEE must be held in the palm of the user's hand on the side opposite the tether point with the tether point facing the user. The appropriate detection bar, either flat or curved depending on the handrail, should be facing down. These detection bars are color coded for convenience. The user can then choose a face of the handrail that aligns with the downward facing detection bar and begin detection by running the detection bar along the chosen face. While the detection bar can be run along the handrail in either direction, top to bottom with respect to the astronaut's position is ergonomically ideal.

When run along a handrail, the detection bar will catch on sharp edges, causing it to rotate out which alerts the user of the encountered sharp edge. The positions of the detection bar before detection and after detection are shown in Fig. 11. The smoothing stone can then be rubbed against the sharp edge, reshaping and smoothing it down until resistance is no longer felt. After attempting removal of the sharp edge, the detection bar can be rotated back into place by hand. Detection should resume a few inches prior to the encountered sharp edge. This allows the user to confirm the sharp edge has been removed. If the detection bar is triggered on the same edge, it means that the sharp edge was not successfully removed and the user can reapply the smoothing stone. If the detection bar does not catch, the sharp edge has been successfully removed and detection can continue.

After completing work on a face of a handrail, the user should run the detection bar along the entire face one more time to ensure that no sharp edges were missed before moving on to the next face. When moving between flat and curved faces of a handrail, SHIRLEE must be flipped and regripped so the correct detection bar is used. When rotating SHIRLEE the tether point should always face the user. SHIRLEE is durable and requires no specific post-use maintenance. However, we recommend inspecting SHIRLEE periodically and replacing any depreciated parts.

III. Device Validation Testing

A. Testing Conditions

Prior to NBL testing, SHIRLEE was tested multiple times. Many of these tests were to gauge and improve functionality, but two tests were conducted with the goal of measuring the effectiveness of the device. For the first of these two tests, 15 sharp edges were simulated on pieces of aluminum. Of these 15 sharp edges, all 15 were detected and 12 were successfully removed after one attempt with the smoothing stone. For our second test 15 sharp edges and an additional 5 smooth bumps were simulated. These smooth bumps, which were also part of the NBL test setup, were raised but not sharp. The goal of these was to ensure that detection only occurs for edges that are sharp and actually pose a threat to the astronauts. 14 of the 15 sharp edges were successfully detected and removed after one attempt with the smoothing stone. Additionally, 3 of the 5 smooth bumps were detected. These were unnecessary detections and show a level of oversensitivity in some situations.

Our testing at the NBL in May 2019 consisted of an NBL diver testing the device in the 6.2 million gallon NBL pool. Before testing, our team presented a Test Readiness Review (TRR) to the NBL safety review board and the NBL Dive Team. Our TRR not only addressed the safety of the physical device, but also included a review of the operations plan, to ensure that the directions given to the diver during testing would lead to accurate and safe usage of the device. Both our device and our operations plan were approved for underwater testing. To ensure diver safety, we met with our diver multiple times prior to the dive to confirm that she understood how to best operate the device.

B. Results

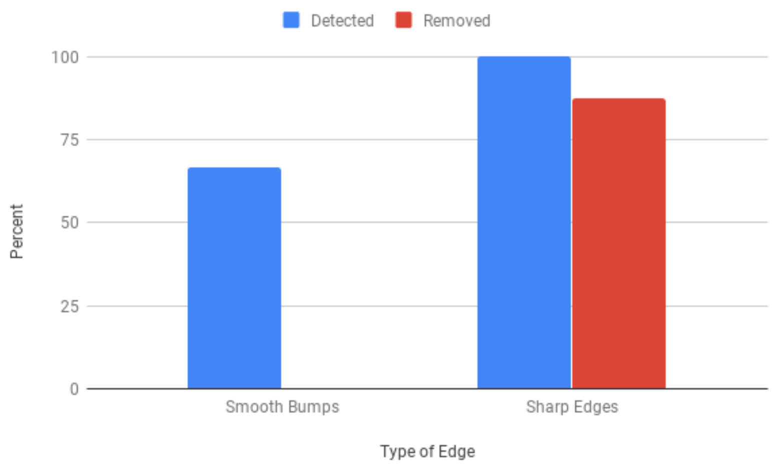

Fig. 12 Results from NBL Testing

The NBL test, for which results are shown in Fig. 12, involved a single handrail with a mix of sharp edges and smooth bumps. Three sharp edges were successfully detected and removed, one on the flat face of the handrail and two on the curved faces. The success of each removal was confirmed with a swatch test. When pressed onto a handrail, the swatch, a small piece of fabric made of a material representative of the tips of astronaut gloves, tears or shows damage if a sharp edge is present. The device passed all swatch tests proving successful removals. After each removal, the sharp edge effectively became a smooth bump. For each, when the detection bar was reapplied to the area, it was not triggered by the former sharp edge, now smooth bump. In addition to the three sharp edges, one smooth bump was detected, which was an overdetection. While removal of each sharp edge was successful, the gold paint on the handrail in the vicinity of each sharp edge was removed, though the metal underneath was undamaged.

C. Diver Feedback

There were two major metrics we used to measure the quality of our design. First, of course, was the quantitative test data, which is discussed in prior sections. The quantitative data tell us that SHIRLEE detected and removed sharp edges successfully. Still, our specific solution is one of many potential solutions to the same problem. To qualify our design as something more than just one of many functional solutions, we consider the diver's experience as an additional metric of tool quality. EVA tools may be technical devices, but they are ultimately designed for humans. Thus, we will take a serious and detailed look at the verbal test feedback we received from our diver [4].

1. Color Coding

SHIRLEE is almost an entirely symmetrical device, with the exception of the two detection bars protruding from either side of the tool. The first detection bar, colored green, was designed to run across the two identical curved faces of the handrail. The second detection bar, colored yellow, was designed to run across the flat face of the handrail. The NBL diver who performed our test expressed that the color coding greatly simplified the entire test procedure. First, it made the diver's experience of learning how to use the device nearly effortless as instructions could be based around

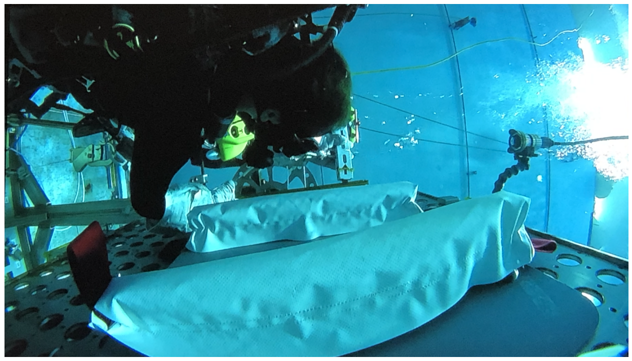

Fig. 13 An NBL Diver testing the device

color matching. During the test we also saw the benefits of color coding pay off. As we read our operations plan to the diver, we did not have to waste time classifying which bar fit where. After the first read through, the diver was naturally fitting the right bar to the right face of the handrail, which demonstrates SHIRLEE's ease-of-use. The benefits of color coding have been shown many times before, but we reaffirm that this design choice greatly simplifies both the initial learning experience and the tool-use that follows.

2. Tether Point and Grip

As shown in Fig. 3 and Fig. 10, SHIRLEE's tether point was placed at the center of the box-shaped tool body. The diver noted that this tether point location made the device easy to grip with EVA gloves. Additionally, she pointed out that this location allowed her to work freely with the tool without the tether invading her workspace. Overall, she felt the tool was easy to grip and natural to hold, even with the constraints of pressurized EVA gloves. As a result of this feedback, we would likely keep the tether point at this location in the middle of the device in any future iterations.

3. The Detection Process: Effectiveness of Detection Bars

The underwater cameras suggested that the flat detection bar, which was run along the flat face of the handrail, fit quite well against the handrail's concavity. Still, given the poor camera quality, we were not certain about the quality of this fit based on visual confirmation alone. We relied instead on the diver's verbal feedback, which confirmed that there was in fact a tight fit between the flat detection bar and the handrail. We believe that this proper fit led to the successful detection of all sharp edges encountered and prevented unnecessary detection of smooth bumps (note that we did not make it all the way to the bottom of the handrail because of time constraints). While the flat detection bar had a tight fit to the bar, the diver expressed that the curved detection bar did not fit quite as well to the curved faces of the handrail it was designed to glide along. Interestingly, we did have one overdetection on a curved face, where we incorrectly classified a smooth bump as a sharp edge. Our hypothesis is that the diver applied more force to the tool on this face to compensate for the slight misfit, which would explain the imperfect detection.

In future iterations, we would not want excess force to potentially cause overdetection, since the tool should be failsafe. To address the overdetection, we would reshape the curved detection bar to fit the concavity of the handrail more tightly. It is worth noting that we were uncertain of the dimensions of the handrail when we constructed our original tool. Armed with the proper dimensions, however, we would be able to correct the shape of the green detection bar with a few simple modifications. Due to the modularity of the design, adjusting this bar would not require remanufacturing the rest of the device, as the single detection bar can be swapped out.

4. The Removal Process: Ambidextrous Application and Level of Exertion Required

After using SHIRLEE to remove a few sharp edges, the diver attempted to switch from her right hand to her left. She was excited to learn that the tool could be used with either hand, however her motive for switching hands raised some concerns. The diver made the switch because her right arm was fatigued. The actual removal process, which involves bending the sharp edge back into place with the smoothing stone, was described as natural and intuitive, similar to the act of erasing and overall comfortable. Still, the fast back and forth motion she was performing was a bit tiring, which is something we hope to correct in future designs.

5. Ergonomic Effectiveness

All things considered, the diver was very satisfied with SHIRLEE, both in terms of her experience using the tool and tool performance. A major design choice we emphasized was simplicity; we wanted our tool to be ergonomic without sacrificing functionality. Whenever we had the option to make something easier or more intuitive while maintaining high quality, we made every effort to do so. As a result of our concerted effort to make our EVA tool intuitive, effective, and simple, we created what proved to be a highly ergonomic device. Many of our comments from the diver expressed satisfaction with regards to this aspect of our design process.

IV. Future Iterations

A. Smoothing Stone Shape

As discussed above, diver feedback showed that using the smoothing stone caused some fatigue, something we would like to improve in future iterations of the design. To reduce diver exertion, our idea is to replace our current smoothing stone, which is in the shape of a rectangular prism, with a cylindrical smoothing stone as depicted in Fig. 14.

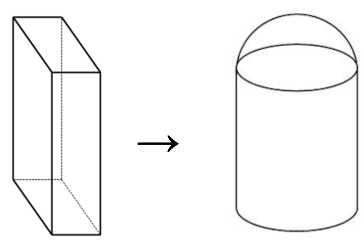

Fig. 14 A possible modification of the shape of the smoothing stone

With this modification, the diver would be able to perform a circular rubbing motion, rather than a back and forth rubbing motion which would reduce arm fatigue. This would also potentially help with the problem of unintended paint removal, discussed below, as it would be more accurate to the sharp edge, cover a smaller area, and therefore remove less paint.

B. Effect on ISS Protective Paint

The protective paint on the exterior of the ISS is crucial in maintaining the temperature inside the ISS. When debris creates sharp edges, some of this paint is removed. When our device removes a sharp edge, additional paint is removed in the vicinity of the sharp edge. Updating the shape of the smoothing stone, as discussed previously, would reduce the amount of paint removed during a removal. To further combat this problem, we recommend covering relevant areas with reflective tape after removing a sharp edge. This tape functions similarly to the paint on the outside of the ISS and would eliminate this hazard.

C. Access and Drainage Holes

One side of the device body has two large holes, designed as access holes so the smoothing stones resting in the interior of the device could be reached and replaced as needed. While the open ends on either side of the device allow for the free flow of air and water, these access holes also served as extra drainage holes, but pose a hazard for finger entrapment. Because the smoothing stones can be easily accessed and replaced from the ends of the device, an access component of the device is no longer necessary. Though operating the device does not require any interaction with or around these holes, removing the holes in future iterations would eliminate the possibility of finger entrapment entirely. But rather than removing the holes completely, in future iterations we would recommend a grid of small holes. This would eliminate any risk of entrapment while still allowing an additional drainage point for air and water.

D. ABS vs. PLA Plastic

While the device can be 3D printed with a variety of materials, our manufactured device used PLA plastic. PLA plastic is brittle and when it breaks it can create sharp edges on the device. Though SHIRLEE has proven to be quite durable, a break could pose a risk to the user. Therefore, in future iterations, we recommend using ABS plastic to manufacture the device, which if broken does not form the same sharp edge risk, eliminating this potential hazard.

V. Conclusion

SHIRLEE's low-cost localized detection and removal of sharp edges would be able to restore full use of ISS handrails, by permanently removing the sharp edges from handrail surfaces. Of greatest significance, the elimination of these sharp edges would greatly increase astronaut safety during EVAs by eliminating a major source of EVA glove damage and providing a more methodical sharp-edge detection method than current visual detection strategies. Full restoration of ISS handrails would also greatly simplify the EVA process by reducing reliance on the IIMS to plan astronauts' maneuvers around sharp edges. The design also shows potential in other extreme environments, such as deep underwater, where the deburring of submarines is similarly challenging.

Our design also highlights the value of 3D printers as a resource on the ISS. Through the use of 3D printers, the majority of our tool could be quickly printed and assembled aboard the ISS. Parts can also be replaced and modified as needed, and this can save on space by storing 3D filament and printing when needed rather than housing fully assembled device components. Our device shows that a functional EVA tool can be made almost entirely out of plastic, which means future space exploration tools could replicate our design principles of simplicity, modularity, and the use of plastic and gain the benefits of onboard-ISS assembly.

Acknowledgments

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