ABSTRACT

Endoscopic tools are widely used for removal of a foreign object from hard-to-reach areas in various applications including medical ones. However, metallic grabbers typically used for such endoscopic removal always bear the risk of accidentally damaging surrounding surfaces or losing the grabbed object. Use of flexible grabbing systems such as a net would greatly reduce such risks by gently handling the object and yielding upon contact with the surroundings. In this study, a new object removing plan using a flexible grabbing system with object-locking is presented along with its realization through a pneumatically operated net and designated hook.

METHOD

Figure 1 illustrates the proposed object removal scheme, using a netting system consisting of a solid hook, a flexible net, and the actuators to bend the net. First, an endoscope carrying the net device and the hook within it approaches the object to be removed (Figure 1a). Then the net device protrudes from the endoscope (Figure 1b) and bends into a full “U”-shape around the object (Figure 1c). Next, the hook extends past the net (Figure 1d). After the net is unfurled to establish contact with the hook (Figure 1e) by switching off the actuators, the hook retracts back until the net is clasped (Figure 1f). With this lock engaged, the entire system is pulled out along with the grabbed object (Figure 1g).

This netting system systematically uses the space available above and below the lodged objects, especially flat ones (e.g., a coin), and avoids accidental nicking or scratches on any surrounding surfaces. Also, the object retraction relies solely upon the strength of the net after it is clasped by the hook, instead of frictional grasping force as in standard forceps. This is especially advantageous when a microactuator is to be used because only the actuation force to deploy the flexible net, which is significantly less than that needed to directly grab and drag the object, is required. Moreover, by wrapping the grabbed object from below, with the net securely hooked to the system, the chance of losing the object during retraction is greatly reduced.

Figure 1: Object removal scheme using a pneumatically activated net and a hook. (a) A tube with the net and the hook approaches the object to be removed, (b) the net protrudes past the object, (c) the net bends inwards to surround the object, (d) the hook extends past the net, (e) the net is unfurled (i.e., net actuator is turned off) to contact the hook, (f) the hook retracts and clasps the net, and (f) the entire system is pulled out along with the object.
DESIGN

For the out-of-plane bending motion of the net in this study, a biocompatible balloon-type pneumatic actuator [6, 7] was used for its inertness and flexible operations. Using a series of such actuators as shown in Figure 2, any bending angle of a finger can be obtained by applying compressed air to the balloon knuckles, curving the net sitting on the top as a result.

![Figure 2: Pneumatically bending net device. An active finger consisting of parylene balloon knuckles between silicon phalanges is operated by compressed air. (a) When no air pressure is applied to the balloons, and (b) when compressed air is applied to bend the attached net.](image)

For 180° of total bending of the net into the “U”-shape, individual fingers approximately 11.5 mm in length with 9 balloon knuckles, each stably establishing 20° deflection, are used in this study, as shown in Figure 3. Each 1300 µm × 730 µm balloon knuckle rotates the attached 1200 µm × 600 µm silicon phalanges.

For successful realization of the proposed object removal plan, the net must be well-aligned and securely attached to the fingers. To achieve this, the net is monolithically fabricated into the system, instead of being glued or manually assembled, by patterning an extra-thick parylene layer into the net shape. Such a net, 18 mm in diameter and 8 µm in thickness, is to be deployed by 5 fingers integrated underneath, and is designed to cover enough area to surround an object (i.e., a coin).

NET STRENGTH TEST

Since the most probable scenario for our device to lose hold of the object is a physical breakage, the weakest element in the system (i.e., the thin-film net) was first tested for its strength. A simple (i.e., no actuator) parylene net exactly the size of the one explained in the previous section was fabricated, as shown in Figure 4a. The opening area for the hook on the net is reinforced by applying epoxy or a tape piece cut into shape to prevent breakage around that area, which is avoidable through similar reinforcements during actual device operations. The net’s strength was tested using a bottle gradually filled with water as in Figure 4b, and the test showed that the net could sustain up to approximately 5 N of force.

![Figure 4: Strength test for the net: (a) a fabricated net (without actuators), (b) a bottle being gradually filled with water held by the net, and (c) close up view of the circled area of (b).](image)

FABRICATION

The fabrication process of the netting device for foreign object removal is shown in Figure 5. A silicon wafer 150 µm in thickness with 3000 Å-thick thermal oxide on the top and bottom surfaces is used as a starting material. The bottom oxide layer is patterned, and the exposed silicon material is anisotropically etched using deep reactive ion etching (DRIE) (Figure 5a) to make trenches. An additional oxide layer is grown by thermal oxidation to conformally coat the trench surfaces (Figure 5b). This layer protects the vertical sidewalls of the trenches during the final device releasing step. Then top-side oxide layer is patterned to make 8 µm × 8 µm openings in the areas where the balloon knuckles are to be formed, followed by isotropic silicon etching through those openings by XeF₂, making molds for balloons (Figure 5c).

After the above steps, 8 µm-thick parylene – the balloon material – is conformally deposited on all the exposed surfaces to form the balloon knuckles and the net, which is made by patterning the deposited layer on the top into the net shape (Figure 5d).
The bottom side oxide layer is anisotropically removed by reactive ion etching (RIE) to selectively etch the oxide under the flat bottom surfaces, yet keeping the oxide on the trench sidewalls [6, 7]. Then the wings of the parylene net patterned on the top are lifted up and detached from the underlying oxide layer in order to prevent warping (due to the stress difference between the parylene and oxide layer) when the device is released (Figure 5e). As the final step, XeF₂ isotropic etching from the bottom side removes the remaining silicon material under the net wings, releasing the fabricated device at the same time (Figure 5f).

The top photo in Figure 6 shows a fabricated device immediately after the releasing step. The bottom photo shows a device bent into the “U”-shape at 50 psi of compressed air, seen from the side.

**DEVICE TEST AND OPERATION**

A plastic cube package with an air inlet hole connected to the attached tube is glued to the fabricated net device for air supply from a nitrogen tank. This assembly is subsequently packaged into a carbon fiber tube 15 mm in overall diameter along with the metal hook as shown in Figure 7 to mimic an endoscope (to be used for future clinical applications). The translation of the net device and the hook is controlled at the other end of the tube.

Figure 8 shows the procedure for object removal using the packaged device and the corresponding net-hook status for each step. First, to remove the object (a button cell battery, CR2030) lodged in a transparent PVC tube (Figure 8a), the packaged device approaches with the net device kept in the tube with its side-wings folded across the longitudinal axis of the tube, resting against the inner surface (Figure 8a-1). This keeps the net straight by preventing bending in the other direction, and minimizes unnecessary exposure of the net during the approach to the target object. When the tube is close enough to the object, the net device protrudes out from the tube (Figure 8b and b-1) and moves past the object. The net surrounds the object by turning the actuators on, followed...
by net-clasping by the hook (figure 8c and c-1). After the object is locked in, the entire tube apparatus is retracted back to remove the object (Figure 8d and d-1).

CONCLUSION

Advantages of using a flexible handling system over solid mechanical grippers to move or manipulate an object include gentle handling of the object and minimization of damage to any surrounding surfaces. The flexible net-based pneumatic object removing tool introduced in this study features a systematic process to lock in an object that is lodged in a tight space by using a designated hook, which ensures a secure holding of the grabbed object by supporting it from below. With these advantages, an object removal tool with the device made by MEMS fabrication technologies would be a great substitution for endoscopic grippers or nets used for various medical endoscopic removal applications, where both safety and grabbing performance matter.

ACKNOWLEDGEMENT

Authors thank Mr. Doug Bernstein for his work on designing and machining the parts used in the tube package, Mr. Guangyi Sun for his help on the device illustrations, and Mr. James Jenkins for discussions regarding the assembly of the paper. This project has been supported by the NIH SBIR program.

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