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Miniature netting system for endoscopic object retrieval from hard-to-reach area

Wook Choi, Vladimir Rubtsov, and Chang-Jin "CJ" Kim

Abstract—**Retrieval of an object from hard-to-reach areas requires the use of instruments of various kinds sent through an endoscope. However, removing a flat object firmly lodged in a narrow space, such as a coin or a button battery in a digestive passageway causes complications when using existing endoscopic instruments. To address such a difficult situation, this paper reports development of a miniature retrieval device using MEMS technology and implementation of the device in a custom-made endoscope. The MEMS device consists of a circular plastic net 15 mm in diameter and pneumatically operated micro-joints integrated under the net to bend it. The endoscope is equipped with a hooking mechanism, which secures the net after it wraps the object, and double imaging systems through which the operator monitors overall endoscopic retrieval procedures. Object retrieval is tested in a lab environment using a coin in a tube.**

Index Terms— **Pneumatic microactuator, endoscope, object retrieval, microhand**

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I. INTRODUCTION

The late 20th century witnessed dramatic advances in imaging and fiber-optic technologies, which improved the optical performance of endoscopes significantly [1]-[3]. Today, endoscopy has become an indispensible tool for both remote visual inspection and remote object manipulation in various fields including medical and industrial [4]-[5]. A user at the proximal end of the endoscope would operate an object-handling instrument at the distal end for various physical and chemical tasks on a small scale [6]-[9]. Those tasks include the retrieval of an object from difficult-to-access areas, such as an accidentally swallowed foreign object (i.e., a coin or button-cell battery) lodged in the esophagus, which requires prompt action by doctors using endoscopic instruments.

Infants' swallowing of a small coin or battery is a common pediatric problem [9]-[12], but is nonetheless regarded as a medical emergency, as damages to the digestive system can occur if not removed in a timely manner [11]-[13].

Mechanical grasping forceps are the most widely used instrument for such esophageal removal treatments [14], [15]. However, the use of forceps requires application of a precise grabbing force, which relies on the operator's previous experience, except in limited attempts to add force feedback capabilities to the grasper [16], [17]. This difficulty could result in accidental loss or deformation of the grabbed object if it is not grabbed properly, leading to even more serious consequences. Completely wrapping around the target object rather than grabbing it, endoscopic retrieval nets [15], [18] provide a safer and more reliable removing process. However, if a flat object is firmly lodged, pushing against the esophagus walls as illustrated in Fig. 1, the existing nets cannot easily surround the object; instead, the object needs to be pushed further down to an open area, e.g., stomach, where the net can operate properly [10].

In this study, we report the development of an endoscopic retrieval system with a miniature netting system, which can be passed through the limited available spaces around the lodged object while maintaining the secure and safe retraction of the netting mechanism. To achieve the goal, we have developed an active-bending net using micro electro-mechanical systems (MEMS) technology. Based on the object-removal plan and the proof-of-concept device introduced at a technical conference [19], an endoscope system has been professionally manufactured for this study to show how a MEMS device can be integrated in a conventional endoscope to enhance its performance. The custom-designed endoscope has an instrument channel to house the microfabricated netting device and two imaging systems.

II. OBJECT RETRIEVAL PLAN

Figure 2 illustrates the object-retrieval plan used for this study where an endoscope with an active-

bending net and a hook is used to wrap around an object from below. First, the endoscope locates and approaches the object with the help of one of the two imaging systems looking along the endoscope's longitudinal axis. When the endoscope gets close enough to the object, the straightened net comes out of the endoscope housing as in Fig. 2 (a). The net passes by the object through one of the two unobstructed spaces between the object and the surrounding wall, as illustrated in Fig. 1, without scratching the wall. The net then bends into a U-shape to surround the object as the bending actuator is turned on, with the hook subsequently protruding from the housing as shown in Fig. 2 (b). Using the second imaging system placed with the netting device to observe the hook, the bent net is securely clasped by the hook as the net is slightly unfurled by turning the actuator off, as in Fig. 2 (c). As a final step, the object, the net, and the hook are all removed when the entire endoscope is pulled out as shown in Fig. 2 (d).

This endoscopic retrieval plan features (1) safe handling, as the object is not damaged by improper grabbing, (2) secure object removal, as the object does not slip out of the net during the retraction, and (3) net deployment through only the available spaces between the lodged flat object and the surrounding walls, unlike conventional clinical retrieval nets. Also note that once the net surrounds the object and gets hooked the retrieval system becomes a passive structure and not affected even if the active MEMS device is damaged during the retrieval through the esophagus.

III. DESIGN: PNEUMATIC NETTING DEVICE

A. Out-of-plane bending principle

To realize the object-removal plan introduced in the previous section, an actuator that can bend out-of-plane into a full U-shape (180˚) is required. There have been several out-of-plane MEMS actuators [20]-[23], but they mostly show a limited actuation range or involve electricity or heating which can interact with a biological environment. Large out-of-plane motion by pneumatic actuation using expansion of balloons introduced by several researchers [24]-[27] is safer owing to its passive nature (i.e., not affecting the objects thermally or electrically) and, therefore, is a good candidate for biological applications. In this study, we employ such pneumatic actuation to bend the net.

Figure 3 shows the net-bending principle using a series of pneumatic balloon actuators. Solid blocks are connected by polymer balloons, which are connected to a compressed air source. On the top is a net made from a relatively thick polymer layer. When no pressure is applied, the solid blocks line up flat under the net as shown in Fig. 3 (a). However, if compressed air is applied to the polymer balloons, they expand, resulting in the out-of-plane bending of the attached blocks – as well as forming the attached net – into a U-shape, as in Fig. 3 (b).

B. Netting device design

The miniature netting device consists of a net, balloon actuators, and the solid blocks, all integrated in one fabrication process to avoid the need for any manual assembly of each part, as illustrated in Fig. 4. The circular Parylene net, 1.5 cm in diameter, is supported by 10 serial silicon knuckles, each to be bent out-of-plane by four parallel Parylene balloons 1100 μm × 510 μm × 30 μm in dimension as fabricated. Such wide knuckles holding a group of parallel balloons ensure uniform bending of each knuckle and greatly increase the resistance to sideway stretching of the net when pulling the object during retrieval compared to the preliminary device introduced in [19]. The bending angle of each silicon block at a given air pressure is identical because all the balloons share the same pressure through a common line and bulge the same amount.

At the end of the net is the opening for a hook. The opening area is reinforced with the attached silicon plate underneath (1) to straighten that area to make hooking easy, (2) to make the opening visible to the second camera embedded to monitor the net clasping process in real time, and (3) to strengthen the area against tearing by the hook during the object retrieval.

With the given net design, the thickness of the net needs to be determined depending on the applications as each application will require a different retrieval force. Through simulated force tests by a pediatrician in a lab-environment for this study as shown in Fig. 5, it was estimated that up to 4.5 – 5.0 N of pulling force was applied during the real coin retrieval from esophagus. Based on the test result in [19], the thickness of the net in this paper was chosen to be roughly 10 μm to sustain the 5 N of force.

IV. DEVICE FABRICATION

The fabrication process of the object retrieval device, illustrated in Fig. 6, is in part similar to that of the UCLA Microhand [25], [26] and consists largely of three steps – actuator definition, balloon formation, and device release. Although the cross section is taken along $\overline{AA'}$ in Fig. 4, only two balloons are shown for clarity. A silicon wafer 150 μm in thickness is used as a starting material, where 3000 Å silicon dioxide layers are thermally grown on the top and bottom surfaces (Step (a)). After the bottom oxide layer is patterned, trenches in the wafer backside are etched by deep reactive ion etching (DRIE) to define the out-of-plane bending actuators (Step (b)). The trenches are 120 μm deep, leaving the 30 μm-thick silicon material on top unetched for later balloon actuator formation. A 600 Å-thick oxide is then grown to protect the etched silicon trenches' sidewalls (Step (c)).

The top oxide layer is patterned by reactive ion etching (RIE) (1) to make 8 × 8 μm square openings in

the area where the balloon actuators will be located, and (2) to make a circular oxide opening 500 μm in diameter where the air inlet is to be made (Step (d)). The subsequent XeF_2 gas introduction through those oxide openings isotropically etches the silicon material underneath to make the molds for balloons and the air inlet (Step (e)). The etching in this step is done until the oxide layer grown on the trench bottom during Step (c) gets exposed to ensure uniform mold depth. Using this oxide layer as the XeF_2 etch stop has greatly increased the fabrication yield, over the previously introduced balloon-forming methods on silicon [25], [26], by fundamentally preventing accidental through-hole formation. An 11 μm-thick Parylene layer is then conformally deposited (Step (f)) to form (1) balloons and the microchannels at the same time, and (2) the net on top of the device. As a result, 4 μm-thick balloons and microchannels, and the 11 μm-thick top layer, which becomes the net, are formed.

After the deposited Parylene is patterned to define the net and to clear the air inlet, the wafer backside is processed using RIE to selectively remove only the oxide on the trench bottom surfaces while the oxide on the trench sidewalls is left unetched (Step (g)). The netting device is finally released by additional XeF_2 etching from the wafer backside (Step (h)). Due to the remaining oxide on the trench sidewalls, the silicon phalanges between each balloon are protected so as to not lose contact with the attached balloons during this isotropic etching process. When the device is attached to the endoscope, which will be introduced in the next section, and the compressed air is delivered through the air inlet, all the balloons connected by microchannels swell and bend the device out-of-plane (Step (i)).

Of note during the fabrication is the need to physically detach the wing section of the Parylene net right before the device release (Fig. 6 (h)). Figs. 7 (a) and (b) are the cross-sectional drawings when the device is cut along $\overline{BB'}$ in Fig. 4, corresponding to Figs. 6 (g) and (h), respectively. If the net's wing is not detached from the underlying oxide layer, as in the left part of the wing in Fig. 7 (a), it will curl up due to the stress mismatch between the Parylene and the oxide layers upon releasing, as shown in Fig. 7 (b). A curled (failed) net and a successfully detached net with curling prevented are shown in Figs. 7 (b-1) and (b-2), respectively.

Fig. 8 is a photo of the fabricated netting device. Every single moving silicon structure is anchored to the Parylene net by square pits made on the silicon during the XeF_2 process in Fig. 6 (e) to ensure secure net attachment during operation.

Fig. 9 shows the bending of the fabricated net as the applied air pressure increases. Fig. 9 (a) is when no pressure is applied, while Figs. 9 (b), (c), and (d) are when 5 psi, 10 psi, and 18 psi are applied to the device, respectively. The net curls to 36° initially at 0 psi, 75° at 5 psi, 118° at 10 psi, and eventually into the full U-shape (180°) to be later clasped by the hook at 18 psi of applied pressure. The force generated by the fabricated netting device is measured by lifting a weight on an electronic scale, as shown in Fig. 10.

Up to 2.4 mN of force was measured at 30 psi. Note that such force is only for bending the net before getting clasped. That is, no force from the microactuators is used to hold the grabbed object during retrieval.

V. ENDOSCOPE SYSTEM

A. Endoscope for object retrieval with MEMS device

To study the feasibility of the fabricated MEMS netting device for future clinical applications, an endoscope system has been custom-designed and professionally manufactured (OMEX Technology, IL), as shown in Fig. 11 (Top). The endoscope is composed of three sections: a metal housing at the distal end, a handle at the proximal end, and a flexible part between them. The length of the endoscope excluding the handle part is 30 cm. The netting device and the hook are accommodated in the metal housing and controlled by the two sliding levers on the handle. The housing has a U-shaped slot in the longitudinal direction so that the net in it is kept straight longitudinally until the net emerges from the housing for operation. Such net-straightening assists the netting device to translate beyond the object through the tight spaces around the object.

The endoscope is equipped with two separate imaging systems, each consisting of an objective lens part, an imaging fiber bundle, a transducer lens, and a CCD camera. With the objective lens placed at the end of the metal housing, the 1st imaging system is to illuminate and show the area in front of the endoscope for conventional inspection, as pictured in Fig. 11 (Bottom). Using the objective lens with a 45˚-angled mirror in front at the base of the net, the 2nd system is to illuminate and show the netting operation. Each imaging system has its own illumination, but the two share one light source and one image-recording computer. The computer displays the two images alternately, showing images from the 1st system while the endoscope approaches the target object and switching to the 2nd system while the net is deployed and hooked. A separate PVC hose connects the netting device to the compressed gas tank with a pressure regulator. The overall outer diameter of the endoscope is 9 mm.

B. MEMS device operation in the endoscope

Fig. 12 (a) shows the entire endoscope held by an operator at the handle, and Fig. 12 (b) magnifies the endoscope's distal end to demonstrate the deployment and hooking of the net. When the netting device comes out from the housing, as shown in Fig. 12 (b-1) (equivalent to Fig. 2 (a)), the net is slightly curved

across the longitudinal direction of the endoscope. When 18 psi of compressed air is applied to the device, the net will curl to form a complete U-shape as in Fig. 12 (b-2). The hook then extends from the housing as shown in Fig. 12 (b-3) (equivalent to Fig. 2 (c)) and locks the net upon removal of the compressed air as shown in Fig. 12 (b-4) (equivalent to Fig. 2 (d)). The endoscope is now ready to retract and remove the object with it.

C. Monitoring the net-clasping

The 2nd imaging system installed at the base of the net is designated to monitor the net-clasping process to ensure hooking before the object is pulled. Fig. 13 shows the images captured during the net-clasping process. Fig. 13 (a) is the image of the hook without the net, while Fig. 13 (b) is the image of the opening at the end of the net when deployed and curled. When the hook is translated to clasp the net after net is curled, the image appears as in Fig. 13 (c). Fig. 13 (d) shows the image after the hook clasps the net.

VI. OBJECT RETRIEVAL BY THE ENDOSCOPE SYSTEM

To test the object retrieval from a hard-to-reach spot using the manufactured endoscope system, a US 5 cent coin lodged in a black PVC tube in water is used as shown in Fig. 14. First, however, Figs. 14 (a-1)-(a-4) visually demonstrate the retrieval plan of Fig. 2 in an empty transparent tube for readers. The straightened netting device approaches the coin with the hook hidden in the housing (Fig. 14 (a-1)). The endoscope gets close enough to the coin that the net-clasping process can be initiated (Fig. 14 (a-2)). The netting device protrudes past the coin to the extent that the 2nd imaging system on the device is not obstructed by the object. At this point the image display is switched from the 1st imaging system to the 2nd. With the help of the 2nd imaging system, the net is bent until the operator sees the net opening, and securely clasped by the hook pushed out from the housing above the other side of the object (Fig. 14 (a-3)). After ensuring the clear locking of the net around the object, the object is pulled out as the endoscope is retracted by the operator (Fig. 14 (a-4)).

Object retrieval under a more realistic condition, i.e., from inside a water-filled opaque tube as shown in Fig. 14 (b), is monitored solely with the 1st and the 2nd imaging systems as shown in Figs. 14 (b-1)-(b-4). During the entire operation, the built-in illumination is turned on to assist the procedure. As the endoscope gets close to the object, the operator detects its location by observing the images from the 1st system (Fig. 14 (b-1)), and slows down the endoscope insertion. When the object is close enough (Fig. 14

(b-2)), the operator fully extends the netting device and the hook, has the net wrap around the object and get clasped to the hook, seeing images similar to Fig. 14 (b-3) from the 2nd imaging system. For this step, up to 25 psi of compressed air is applied to the netting device. During the object retrieval, the operator can make sure the object is not being lost by checking the image of the object as shown in Fig. 14 (b-4), captured by the 1st imaging system.

VII. CONCLUSION

We have developed an endoscopic system aimed toward object removal from a digestive passage. The system is complete with a MEMS-based netting device and a hooking mechanism in a conventional endoscope. The endoscope system in this paper was tested in a lab environment to assess the feasibility for the clinical removal of accidentally swallowed foreign objects from infants' esophagi. At 20 psi of applied pressure, the netting device showed more than 180˚ of bending for retrieval operation, and the entire procedure was monitored by the two imaging systems embedded in the endoscope. Sharing the advantages of secure retrieval by a net, while utilizing the limited available space around the lodged flat object for net deployment, the proposed system is being developed to be a valuable new instrument for endoscopic retrieval procedures.

REFERENCES

[1]   R. A. Miller, "Endoscopic instrumentation: evolution, physical principles and clinical aspects," *British Medical Bulletin*, vol. 42, pp. 223-225, 1986.

[2]   S. J. Spaner and G. L. Warnock, "A Brief History of Endoscopy, Laparoscopy, and Laparoscopic Surgery," *Journal of Laparoendoscopic & Advanced Surgical Techniques-Part A*, vol. 7, pp. 369-373, 1997.

[3]   G. S. Litynski, "Endoscopic surgery: the history, the pioneers," *World Journal of Surgery*, vol. 23, pp. 745-53, 1999.

[4]   A. Cuschieri, "Minimal access surgery and the future of interventional laparoscopy," *American Journal of Surgery*, vol. 161, pp. 404-407, 1991.

[5]   Y.-K. Zhu, G.-Y. Tian, R.-S. Lu, and H. Zhang, "A Review of Optical NDT Technologies," *Sensors*, vol. 11, pp. 7773-7798, 2011.

[6]   J. E. Geenen, D. E. Fleischer, J. D. Waye, R. P. Venu, and B. S. Lewis, "Techniques in therapeutic endoscopy," Gower Medical Publishing, New York, 1992.

[7]   R. Elazary, A. Khalaileh, G. Zamir, M. Har-Lev, G. Almogy, A. I. Rivkind, and Y. Mintz, "Single-trocar cholecystectomy using a flexible endoscope and articulating laparoscopic instruments: a bridge to NOTES or the final form?", *Surgical Endoscopy*, vol. 23, pp. 969-972, 2009.

[8]   S. Dutta, "Early experience with single incision laparoscopic surgery: eliminating the scar from abdominal operations," *Journal of Pediatric Surgery*, vol. 44, pp. 1741-1745, 2009.

[9]   M. L. Waltzman, "Management of esophageal coins," *Current Opinion in Pediatrics*, vol. 18, pp. 571-574, 2006.

[10]   G. G. Ginsberg, "Management of ingested foreign objects and food bolus impactions," *Gastrointestinal Endoscopy*, vol. 41, pp. 33-38, 1995.

[11]   G. P. Conners, J. M. Chamberlain, and D. W. Ochsenschlager, "Symptoms and spontaneous passage of esophageal coins," *Archives of Pediatrics & Adolescent Medicine*, vol. 149, pp. 36-39, 1995

[12]   T. Litovitz, B. F. Schmitz, "Ingestion of Cylindrical and Button Batteries: An Analysis of 2382 Cases," *Pediatrics*, vol. 89, pp. 747-757, 1992.

[13]   T. Litovitz, N. Whitaker, L. Clark, N. C. White, and M. Marsolek, "Emerging battery-ingestion hazard: clinical implications," *Pediatrics*, vol. 125, pp. 1168-1177, 2010.

[14]   B. C. Bounds, "Endoscopic retrieval devices," *Techniques in Gastrointestinal Endoscopy*, vol. 8, pp. 16-21, 2006.

[15]   D. O. Faigel, B. R. Stotland, M. L. Kochman, T. Hoops, T. Judge, J. Kroser, J. Lewis, W. B. Long, W. B., D. C. Metz, C. O'Brien, D. B. Smith, and G. G. Ginsberg, "Device choice and experience level in endoscopic foreign object retrieval: an in vivo study," *Gastrointestinal Endoscopy*, vol. 45, pp. 490-492, 1997.

[16]   T. Hu, G. Tholey, J. P. Desai, and A. E. Castellanos, "Evaluation of a laparoscopic grasper with force feedback," *Surgical endoscopy*, vol. 18, pp. 863-867, 2004.

[17]   J. Rosen, B. Hannaford, M. P. MacFarlane, and M. N. Sinanan, "Force controlled and teleoperated endoscopic grasper for minimally invasive surgery - experimental performance evaluation," *IEEE transactions on Biomedical Engineering*, vol. 46, pp. 1212-1221, 1999.

[18]   M. T. Smith and R. K. Wong, "Esophageal foreign bodies: types and techniques for removal," *Current Treatment Options in Gastroenterology*, vol. 9, pp. 75-84, 2006.

[19]   W. Choi, V. Rubtsov, and C.-J. Kim, "Pneumatically Deployed Net System for Endoscopic Removal of Foreign Object," in *Proceedings of IEEE International Conference on MEMS*, pp. 17-22, Cancun, Mexico, 2011.

[20]   J. W. L. Zhou, H. Y. Chan, T. K. H. To, K. W. C. Lai, and W. L. Li, "Polymer MEMS actuators for underwater micromanipulation," *IEEE/ASME Transactions on Mechatronics*, vol. 9, pp. 334–342, 2004.

[21]   S. W. John and G. Alici, "Towards micro and nano manipulation systems: behaviour of a laminated polypyrrole (PPy) actuator driving a rigid link," in *Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pp. 54–59, Monterey, USA, 2005.

[22]   E. W. Jager, H. O. Inganäs, and I. Lundström, "Microrobots for micrometer-size objects in aqueous media: potential tools for single-cell manipulation," *Science*, vol. 288, pp. 2335-2338, 2000.

[23]   G. Lin, C.-J. Kim, S. Konishi, and H. Fujita, "Design, fabrication and testing of a C-shaped actuator," in *Proceedings of International Conference on Solid-State Sensors, Actuators and Microsystems*, vol.2, pp. 416-419, Stockholm, Sweden, 1995.

[24]   S. Konishi, F. Kawai, and P. Cusin, "Thin flexible end-effector using pneumatic balloon actuator," *Sensors and Actuators A*, vol. 89, pp. 28-35, 2001.

[25]   Y.-W. Lu and C.-J. Kim, "Microhand for biological applications," *Applied Physics Letters*, vol. 89, pp.164101, 2006.

[26]   W. Choi, M. Akbarian, V. Rubtsov, and C.-J. Kim, "Microhand with internal visual system," *IEEE Transactions on Industrial Electronics*, vol. 56, pp. 1005-1011, 2009.

[27]   Y. Watanabe, M. Maeda, N. Yaji, R. Nakamura, H. Iseki, M. Yamato, T. Okano, S. Hori, and S. Konishi, "Small, soft, and safe microactuator for retinal pigment epithelium transplantation," in *Proceedings of IEEE International Conference on MEMS*, pp. 659–662, Kobe, Japan, 2007.

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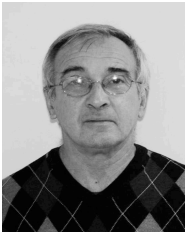
Vladimir Rubtsov received his Ph.D. degree in Applied Physics from Nondestructive Control Research Institute, in Kharkov, Ukraine, (former USSR). His research career in the USA includes positions as: Staff Researcher in the Surgery Dept. Research Laboratory at the UCLA Medical Center (Los Angeles, CA, 1992-2001), and Fiber Optic Program Manager at FarLight Corporation (Torrance, CA, 1996-2000). Dr. Rubtsov joined Intelligent Optical Systems, Inc. (IOS) as a senior scientist in 2000. Dr. Rubtsov's expertise is in non-destructive testing, fiber optic and LED illumination, endoscopy, optical sensors, and fiber lasers development. He has developed devices for the US Navy, the US Army, the National Institutes of Health, National Science foundation, DARPA, Homeland Security, and NASA. He has conducted more than 50 projects, and has four US patents and seven Russian patents.

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Prof. Kim has served on numerous technical committees and panels, including Transducers, the IEEE International Conference on MEMS, and the National Academies Panel on Benchmarking the Research Competitiveness of the U.S. in Mechanical Engineering. He is currently serving on the Editorial Advisory Board for the IEEJ Transactions on Electrical and Electronic Engineering and the Editorial Board for the Journal of Microelectromechanical Systems. A fellow of ASME, he was the recipient of the Graduate Research Excellence Award from Iowa State University, the 1995 TRW Outstanding Young Teacher Award, the 1997 NSF CAREER Award, the 2002 ALA Achievement Award, and the 2008 Samueli Outstanding Teaching Award.
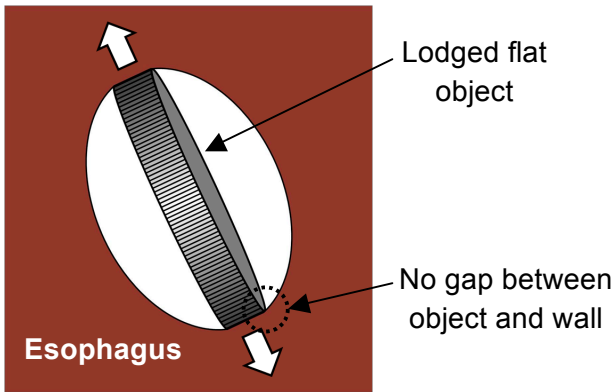
Fig. 1. Simplified cross-sectional drawing of a flat object lodged in esophagus passageway, which may even be stretched. An existing endoscopic retrieval net [15], [18] cannot be deployed around the object, as there is no space to pass through at the two stretched points.
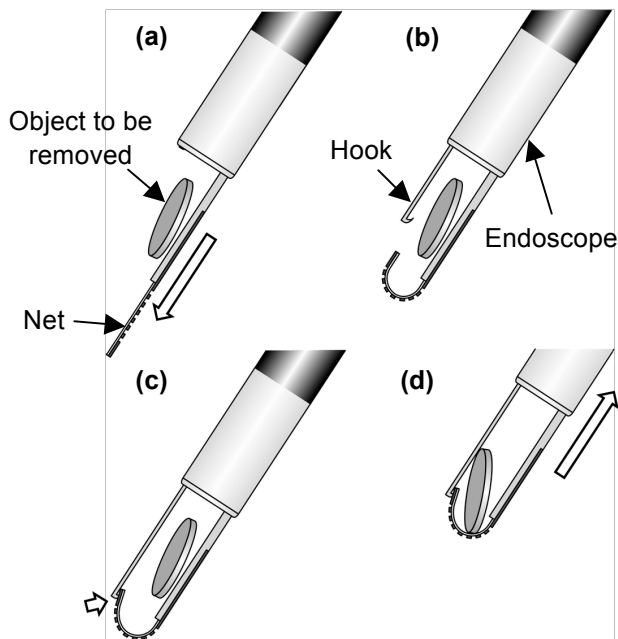

Fig. 2. Endoscopic object-retrieval plan. (a) After the endoscope approaches the object, the net comes out from the housing, (b) the net bends to surround the object and the hook protrudes from the housing, (c) the bent net is clasped by the hook, and (d) the locked object is pulled out as the endoscope retracts.
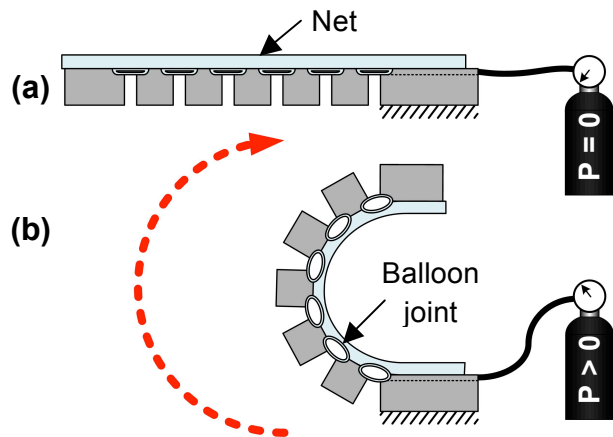
Fig. 3. Net-bending principle. A series of balloon joint systems are used to achieve a U-shape bending of the attached net. (a) When no air pressure is applied to the balloons, and (b) when compressed air is applied to bend the attached net. Expansion of the balloons by the compressed air results in 180˚ bending of the net.
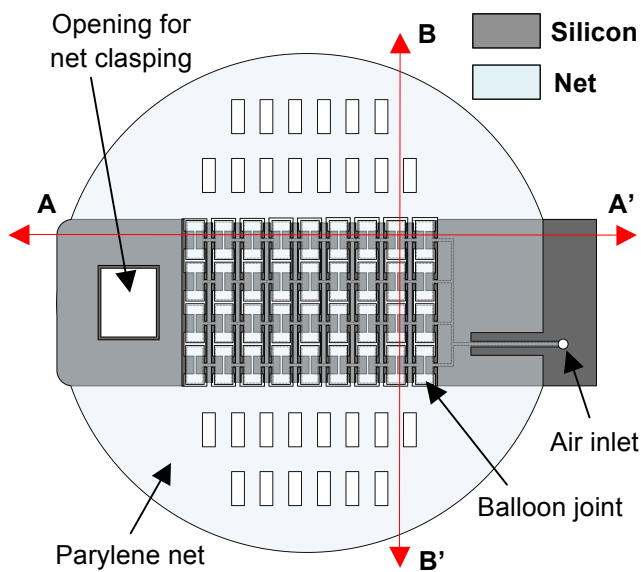
Fig. 4. Simplified drawing of the netting device. A circular Parylene net is attached to a number of bending actuators, which consist of balloon joints and the interconnecting silicon knuckles. Every balloon is connected to the air inlet through a microchannel.

13
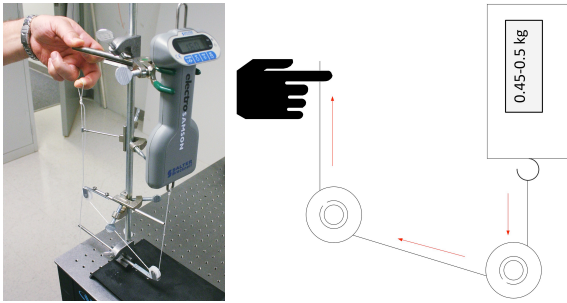
Fig. 5. Pulling force estimation for pediatric coin removal. The procedure was found to require up to 4.5-5 N of forces.
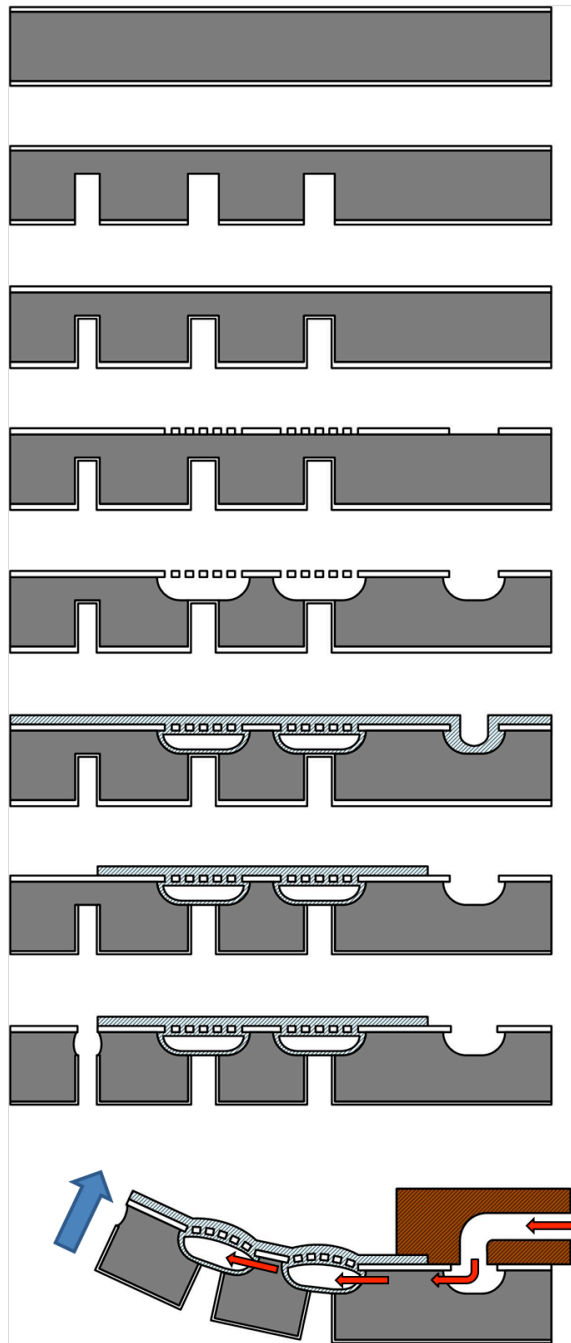
Fig. 6. Fabrication process of the object retrieval device. (a) A 150 μm-thick silicon wafer with thermally grown 3000 Å oxide layers, (b) the bottom oxide layer patterning and anisotropic silicon etching, (c) thermal oxidation for trench sidewall coating, (d) the topside oxide layer patterning, (e) isotropic silicon etching by XeF_2, (f) conformal Parylene deposition, (g) Parylene layer patterning and the oxide removal from the trench bottom surfaces, (h) silicon material etching by XeF_2 to release the finger, and (i) the device operation, i.e., bending, by applying compressed air.
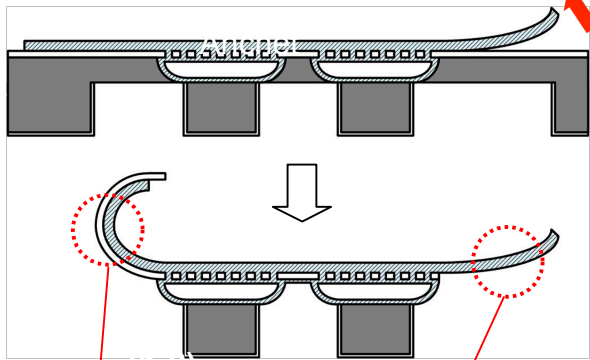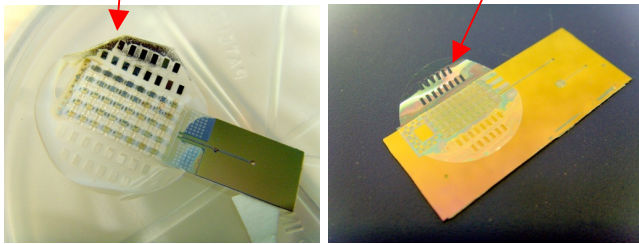
Fig. 7. Detachment of the wing section to prevent warping of the net. (a) The physically detached side (right) and undetached side (left) of the wing before the device release. (b) The resulting shape of the wing after the device release. Due to the stress mismatch between the Parylene and the underlying oxide, (b-1) the undetached net rolls up while (b-2) the detached section stays relatively straight.
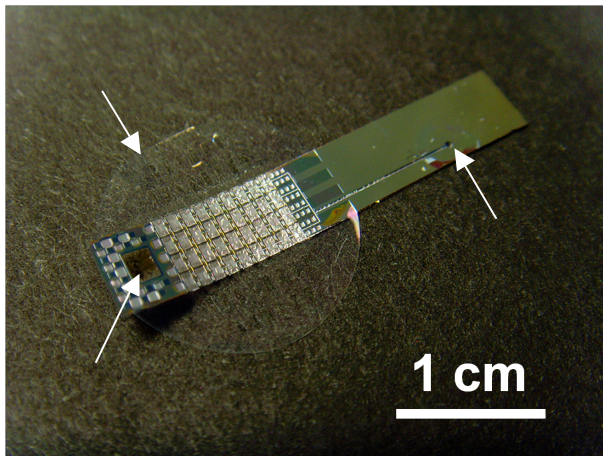

Fig. 8. The fabricated netting device. The Parylene net is 1.5 cm in diameter and 11 μm in thickness, and supported by 10 silicon knuckles connected by a total of 36 balloon actuators.

Weight
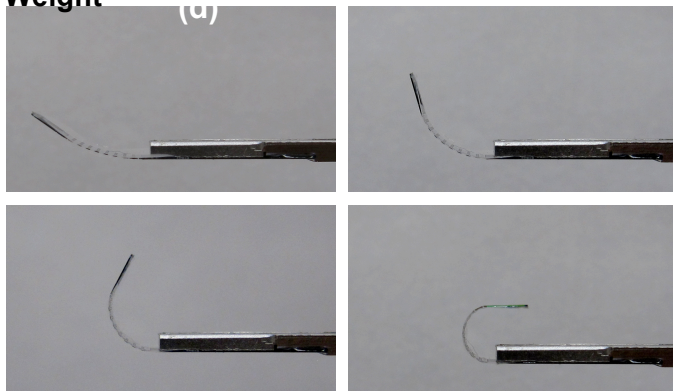
Fig. 9. Bending of the net when compressed gas is applied. (a) When no gas is introduced, (b) when 5 psi is applied, (c) when 10 psi, and (d) when 18 psi is applied where the net bends into the full U-shape.
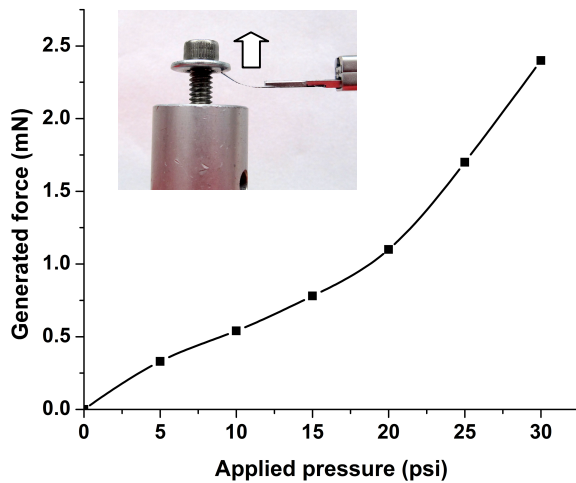

Fig. 10. Generated force to close the net by the fabricated device. A weight on an electronic scale is pulled upward by the netting device. Up to 2.4 mN of force was measured at approximately 30 psi of pneumatic actuation.
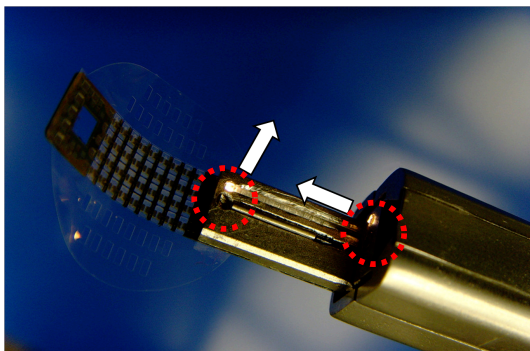
Handle for hook
translation

Netting
device

Flexible tube

Handle for device
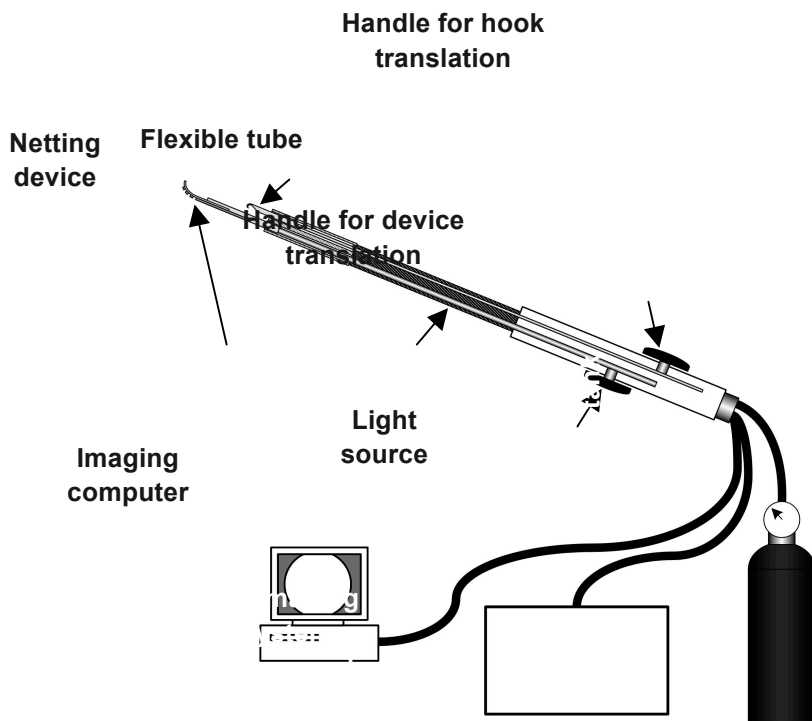translation

Imaging
computer

Light
source

Fig. 11. The endoscope system custom-designed and professionally manufactured for this study. The system consists of the endoscope, a light source, an imaging computer, and the gas pressure source with a controller. The endoscope 9 mm in outer diameter and 30 cm in length houses the netting device and the hook, and is equipped with two endoscopic imaging systems.

(a)   **Flexible part**

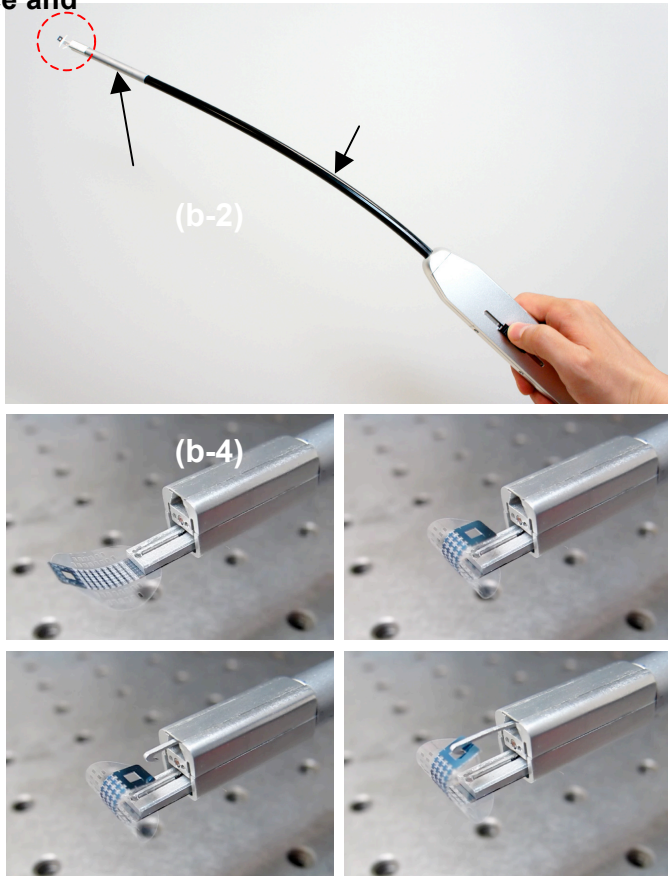**Solid housing for the device and**

(b-2)

(b-4)

Fig. 12. Photos of the endoscope and its distal end, i.e., the tip area. (a) The endoscope held by hand, showing the flexible part and the metal housing. (b-1) The close-up view of the dotted-circled area of (a) when no gas pressure is applied. (b-2) At 18 psi, the net bends into a U-shape. (b-3) The hook comes out from the metal housing, and (b-4) clasps the net.
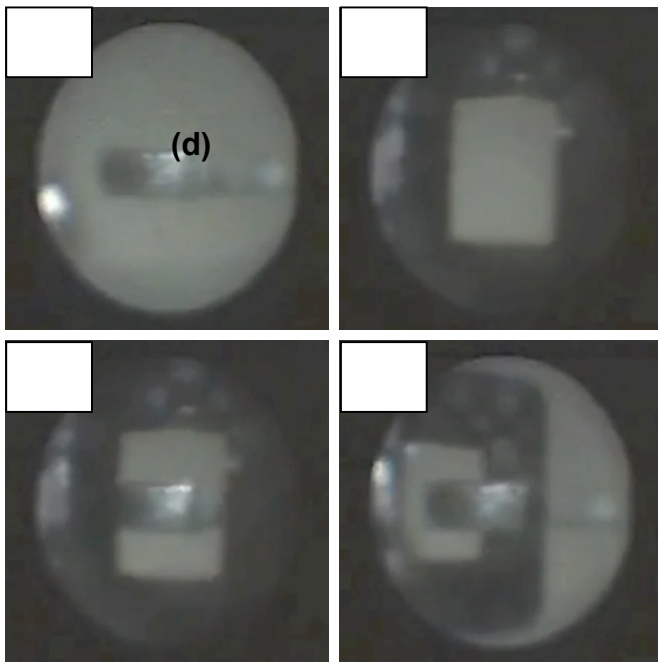
19

Fig. 13. Images captured by the 2nd imaging system looking vertically from the netting device side. (a) After the hook is extended out (net is not deployed for clarity), (b) when the net is fully bent to show the net opening for the hook, (c) when the hook is extended to clasp the net, and (d) after the net is clasped.
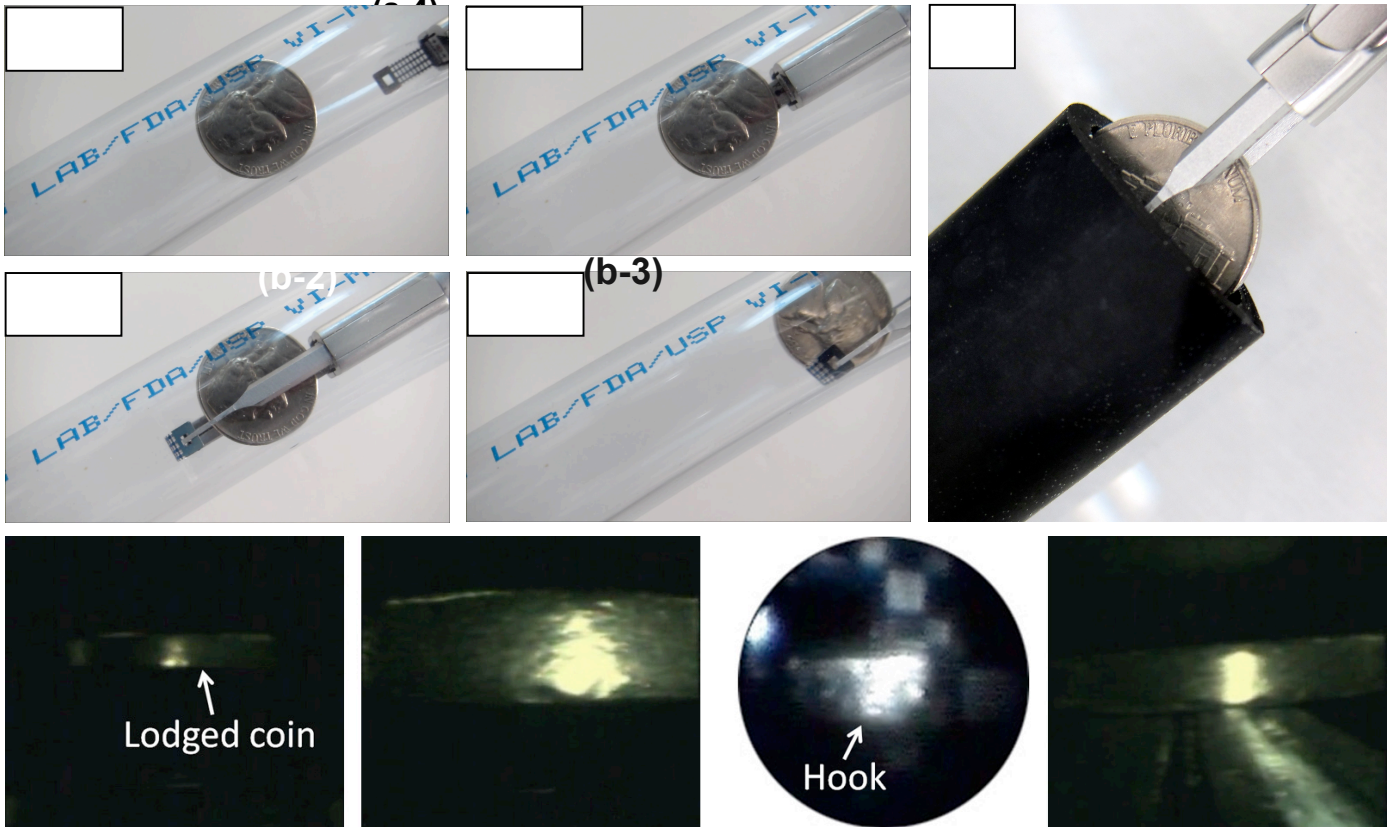
Fig. 14. Coin retrieval experiment using the developed endoscope system and the proposed removal plan. A US 5 cent coin is used for this experiment. (a-1)-(a-4) are representation of the endoscope's each operation step observed through an empty transparent tube. (b) A coin lodged in a water-filled opaque PVC tube is taken out by the endoscope. (b-1) The endoscope locates the object to be removed, as in (a-1). (b-2) The endoscope approaches the coin so that the netting device and the hook can reach the other side of the object when extracted, as in (a-2). (b-3) The 2nd imaging system is turned on for this step. The netting device and the hook stretch out from the housing, and the net is clasped by the hook to wrap the object as in (a-3). (b-4) The locked object is retrieved as the endoscope is pulled back, as in (a-4).