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Compact Design of a Dual Master-Slave System for Maxillary Sinus Surgery

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***Abstract*— The pathway to the maxillary sinus area is anatomically curved and narrow. Thus, using the conventional approach based on the straight endoscope and surgical tools, there are some limitations in inspection and treatment of the target legion of the maxillary sinus. To cope with such problems, a dual master-slave system is investigated in this work for general maxillary sinus surgery. Initially, the need for dual arm operation is explained. A compact design of two 4-DOF end-effector mechanisms for acquiring the endoscopic image and performing biopsy is introduced. Next, a dual master device to control the motions of the two end-effector mechanisms is employed and a motion scheduling algorithm for a proper master-slave control is also developed. Finally, the feasibility of the dual master-slave system is verified through experimental work.**

I. Introduction

A recent trend in surgery is minimally invasive surgery (MIS) and non-invasive surgery like laparoscopic surgery or NOTES (Natural Orifice Translumenal Endoscopic Surgery). Responding to this trend, various surgical tools and robotic systems are being developed in the areas of laparoscopy, urology, neurology, cardiovascular intervention, orthopedic procedures, and so on. However, surgical robotic systems have many limitations yet, especially in the field of otorhinolaryngology [1]. According to the review by clinicians, studies of robotic system applied to sinus surgery have been very few [2]. Thus a robotic system for sinus surgery will be further discussed in this paper.

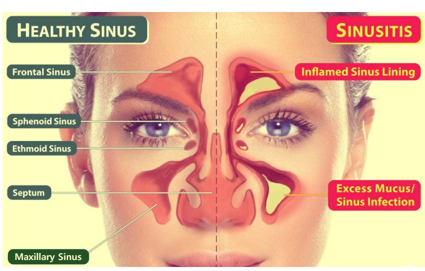

Figure 1. Sinus and sinusitis.

The human skull contains four major pairs of hollow air-filled spaces called sinuses as shown in Fig. 1. They are connected to the space between the nostrils and the nasal passage. Sinusitis is an inflammation of the sinuses, which may be due to infection, allergy, or autoimmune issues. The inflammation causes pus to fill the sinus cavities and then the sinuses cannot function normally. The goal of sinus surgery is to flush out infected material, open up blocked sinus passages, and keep enough healthy tissue so that the nose and sinuses can function normally.

Today, functional endoscopic sinus surgery (FESS) is the most common surgical method to treat the sinusitis. Using the endoscopic device, lesions inside the sinus can be checked and removed through a nostril. However, the front and the bottom parts of maxillary sinus and the inside of frontal sinus are difficult to check and treat because the existing endoscopic devices for sinus surgery are mostly straight. Iro, et al. [3, 4] described the need for a bendable device in sinus surgery. Olympus co. [5] provided a flexible endoscope but it has a limited angle of bending and it is not fixable in a state where it is bent. Thus, a further study is necessary to develop a new endoscopic device which is adjustable in angle of bending.

There have been very few robotic approaches to sinus surgery. Burgner, et al. [6] developed a bimanual tele-operated system for endonasal skull base surgery. The system has a dual robotic arm which is small, bendable, and dexterous. But it is difficult to apply the system to the maxillary sinus surgery because the dual arm has large radius of curvature when it is bent. Rilk, et al. [7] proposed a prototype for robot assisted endoscopic sinus surgery which included useful graphical user interface and navigation system. But a straight endoscope was used for the system. Hanna, et al. [8] performed a transnasal surgery on a cadaver using the da vinci surgical system. However, it is difficult to apply the da vinci surgical system to sinus surgery because of the large size.

Yoon, et al [9, 10] developed endoscopic robot systems for sinus surgery and performed navigation through maxillary sinus area. An endoscope using a spring as a backbone was designed, which has 2 DOF or 4 DOF and can be bent by 180 degrees. The bendable endoscope enables the operator to check the internal status of the maxillary sinus.

Analyzing the conventional endoscopic sinus surgery, we could come to a conclusion that a dual arm robotic system is necessary. The surgeon holds an endoscope by one hand and uses a surgical tool by another hand during the operation to diagnose and treat the target lesions simultaneously. Resultantly, replacing the surgeon's hands by the dual arm robotic system would let the surgeon use his hands for other tasks.

Another concern is the degrees of freedom. In order to fully observe the inside of the maxillary sinus, the endoscope needs more degrees of freedom. The biopsy device also needs

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more degrees of freedom in order to reach and remove the target lesion.

The purpose of this paper is to propose a new dual arm robotic system for diagnosis and biopsy in maxillary sinus area. The maxillary sinus is selected as the target area since it is the most difficult area to inspect due to its complex, curved geometry.

To diagnosis and treat the target lesion of the maxillary sinus, the bendable mechanism should be bent by 180 degrees and has a small radius of curvature. More specially, the newly developing system consists of a 4-DOF endoscope end-effector, a 5-DOF biopsy end-effector, a driving power transfer module, and a sliding module for generating the insertion motion of end-effectors.

This paper is organized as follows. The section II deals with compact design of a dual arm slave system. A master device for dual arm operation is also introduced. Implementation and experimental works are included in the section III. Finally, the section IV draws conclusion.

II. Design of Dual Arm Robotic System

A. Design of dual arm slave system

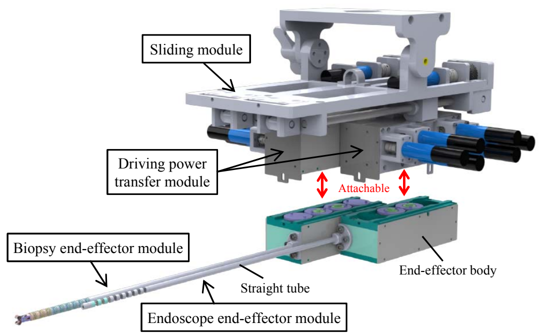


Figure 2. The 3D model of the dual arm slave system.

A dual arm slave system for maxillary sinus surgery proposed in this paper consists of four modules; an endoscope end-effector module, a biopsy end-effector module, a sliding module, and a driving power transfer module as shown in Fig. 2.

For inserting the two end-effectors into the maxillary sinus through a nostril, the two end-effectors should have small diameters and be close to each other. Also each end-effector needs to be controlled independently because the position of the endoscope is fixed sometimes but a surgical tool can be exchanged with other tools during the surgery.

The two end-effectors were designed to fit within a circle of 10 mm diameter due to the anatomical structure of the nostril opening as shown in Fig. 3. A design to arrange the two end-effector mechanisms closely within 1mm is devised to insert them into nostril with a small diameter.

For attaining this specification, a straight tube holding the end-effector is located at one side of the base body of the end-effector module. Inside the end-effector body, some wire guide pulleys are arranged to connect the driving wires to the wire driving pulleys and to adjust tension of the driving wires.

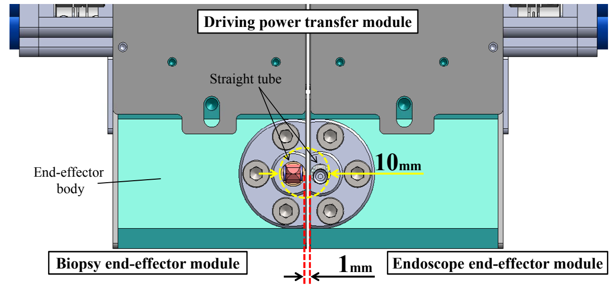


Figure 3. Distance between the two end-effectors.

The driving power transfer module for controlling the continuum mechanism proposed in this work is designed by using coaxial structure which has two driving axles at an axis. Using this structure, we can design the driving power transfer module more compact even though more degrees of freedom are added to the system. Fig. 4 shows the 3D model and the prototype of the driving power transfer module. Its dimension is within a 107x110x36.5 mm volume and the weight is less than 525g.

The end-effector module can be assembled to the driving power transfer module. It can also be disassembled to be sterilized or to be exchanged with other end-effector modules.

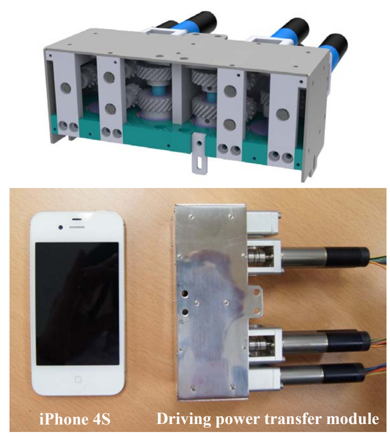
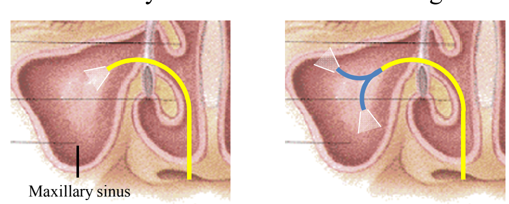


Figure 4. The 3D model and prototype of driving power transfer module.

B. Design of endoscope end-effector

In order to insert the endoscope into the maxillary sinus, the tip of the endoscope should be bent by 180 degrees and should have a small radius of curvature [9]. Such bendable endoscopes allow inspection of a large workspace and even invisible area occluded by the other end-effector, organs, or tissues. In addition, the endoscope needs more degrees of freedom for providing the surgeon with a wider and detailed view of the maxillary sinus area as shown in Fig. 5.



2 DOF 4 DOF

Figure 5. Comparison of a 2-DOF endoscope and a 4-DOF endoscope.

The endoscope mechanism proposed in this paper is a 4-DOF mechanism consisting of two continuum mechanisms as shown in Fig. 6. The advantage of the continuum mechanism is the flexibility of the whole body by using a compliant spring backbone. Thus, even in the case of collision with human body, this device can ensure safety. Each continuum mechanism has 2 DOF. The two continuum mechanisms consist of six and three nodes, respectively. A cylinder and a spring are defined as a node. The base continuum mechanism consisting of six nodes is designed to be bent maximally by 180 degrees and the distal continuum mechanism consisting of three nodes is designed to be bent by 90 degrees.

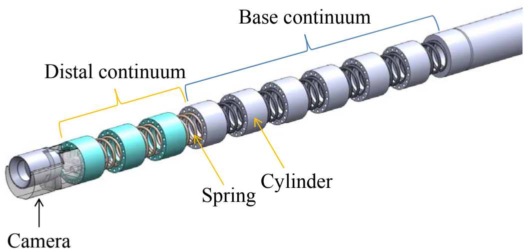


Figure 6. Structure of the endoscope end-effctor module.

C. Biopsy end-effector module

In order to reach and remove the target lesion inside the maxillary sinus, a biopsy end-effector should be inserted more deeply than the endoscope end-effector. Thus, it should have at least 3 degrees of freedom for biopsy motion to reach any target position in the 3-dimensional space as shown in Fig. 7. Thus, the proposed biopsy end-effector is designed to have 5 DOF by assembling two continuum mechanisms and a 1-DOF gripper.

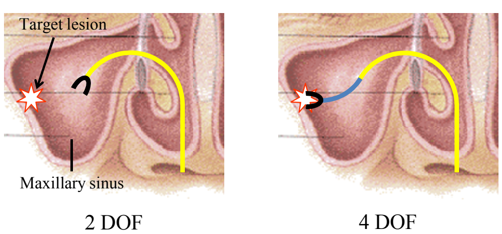


Figure 7. Comparison of a 2-DOF biopsy device and a 4-DOF biopsy device.

Even though the biopsy end-effector consists of two continuum mechanisms like the endoscope end-effector, the design of the biopsy end-effector is different from that of the endoscope end-effector because it should have a considerable payload to biopsy some tissue inside the maxillary sinus area. To increase the payload of the biopsy end-effector, two cylinders are connected by a ball joint as shown in Fig. 8. The ball joint plays the role of an internal backbone and resultantly it increases the stiffness of the continuum mechanism.

The kinematics for continuum mechanisms is already well-known. Walker et al. [11], Webster III et al. [12], Simaan et al. [13], Choi et al. [14], and Yoon et al. [15] presented several kinematic models for continuum mechanisms.

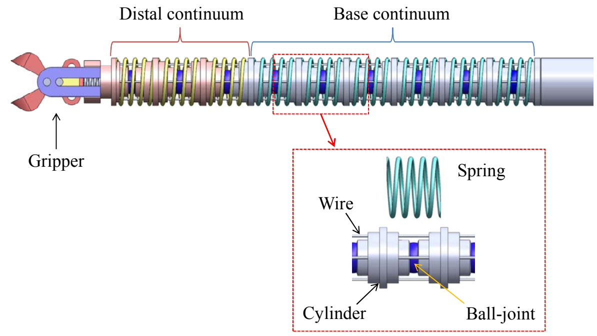


Figure 8. Structure of the biopsy end-effctor module

D. Master device

To control the dual arm slave robot, we employ two USB joysticks as master devices. The motions of the dual arm slave system controlled by the two joysticks consist of 4 DOF motions of each end-effector module, 1-DOF gripping motion of the biopsy end-effector module, and 1-DOF insertion motion of each end-effector module. Fig. 9 describes the motion matching between the master device and the slave robot.

Figure 9. Master device and motion matching between the master device and the slave robot.

In regard of controlling two continuum mechanisms of the end-effector modules, the base continuum mechanism and the distal continuum mechanism are controlled in turn by switching modes. There are three modes for controlling the continuum mechanism; base, distal, and insert. The base mode and the distal mode are to control each continuum mechanism. The insert mode is that the base continuum mechanism follows the route of the distal continuum mechanism when the end-effector module is being inserted into the sinus cavity.

When a user controls the master devices, the control software gets the displacement and the button state information of the master device. Then the control software transforms the information of the master to the information of the slave and then the slave system is controlled in accordance with the user's intention.

III. Implementation

A. Dual master-slave robotic system for maxillary sinus surgery

The block diagram of the entire system is represented in Fig. 10. The system consists of a dual arm slave robot, a controller, a master device, and a main PC including a master/slave control software and a endoscopic image. The master device is connected to the main PC through USB. The controller communicates with the main PC through CAN protocol. The master/slave control software gets the motion parameters of the master device and transfers the control commands to the controller every 10 milliseconds. The operator can control the slave robot by using the master device and the endoscopic image.

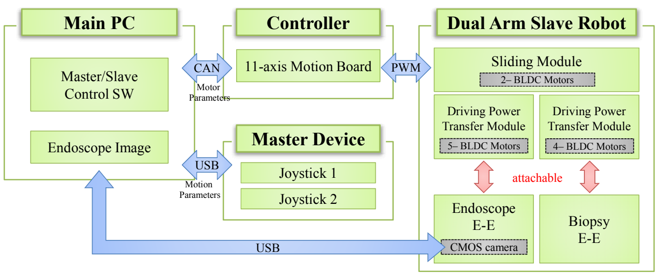


Figure 10. System block diagram of the dual master-slave robotic system.

Fig. 11 shows the prototype of the dual arm slave robotic system. The system consists of a dual arm slave robot and a controller box. The slave robot includes four modules; an endoscope end-effector module, a biopsy end-effector module, a sliding module, and a driving power transfer module. Table I shows the specification of the developed dual arm slave robot mechanism. The dual arm slave robot has two driving power transfer modules each of which has 6 DOF. In this work, 9 degrees of freedom are used because the two end-effectors have 4 DOF and 5 DOF, respectively. For generating motion of the dual arm slave robot, a BLDC motor 1226E012B (9.3W, 12V) and a motion controller MCBL3006S (CAN interface) produced by FAULHABER Co. are employed.

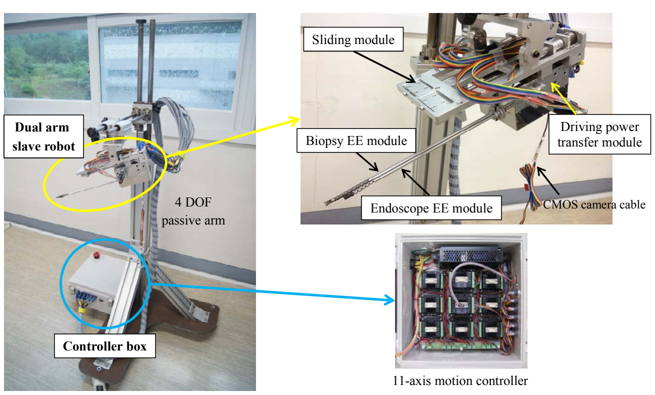


Figure 11. Prototype of the dual arm slave robotic system.

Fig. 12 shows the prototype of the two end-effector modules. The endoscope end-effector module consists of a CMOS camera, two continuum mechanisms (a base continuum and a distal continuum), a straight tube, and an end-effector body. The biopsy end-effector module has a gripper instead of the camera. The diameter of the endoscope end-effector is 4 mm and the diameter of the biopsy end-effector is 5mm. The weights of the two modules are 191g and 252g, respectively.

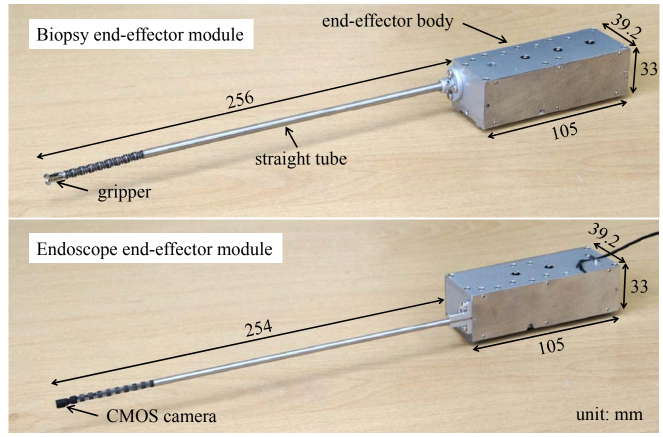


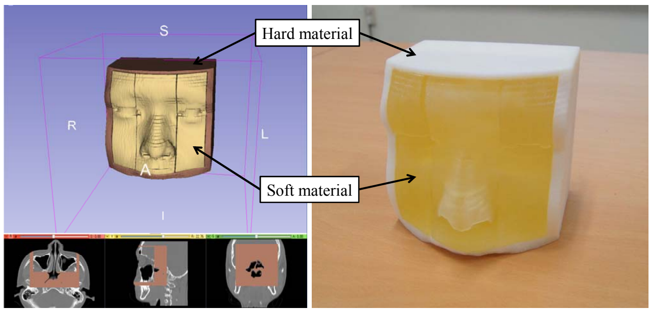
Figure 12. Prototype of the two end-effctor modules.

TABLE I. Specification of the Dual arm slave robot mechanism

Module	Specification	
Endoscope end-effector module	Degrees of freedom	4
	Diameter	4 mm
	Radius of curvature	10 mm
	Azimuth angle of bending	360°
	Length of base continuum	30 mm
	Number of nodes of base continuum	6
	Stiffness of spring backbone(base)	2.0 N/mm
	Bending algle of base continuum	±180°
	Length of distal continuum	15 mm
	Number of nodes of distal continuum	3
	Stiffness of spring backbone(distal)	1.5 N/mm
	Bending angle of distal continuum	±90°
	Length of CMOS camera	8.5 mm
Biopsy end-effector module	Degrees of freedom	5
	Diameter	5 mm
	Radius of curvature	9.4 mm
	Azimuth angle of bending	360°
	Length of base continuum	30 mm
	Number of nodes of base continuum	6
	Stiffness of spring backbone(base)	5.9 N/mm
	Bending algle of base continuum	±180°
	Length of distal continuum	14.3 mm
	Number of nodes of distal continuum	3
	Stiffness of spring backbone(distal)	2.9 N/mm
	Bending angle of distal continuum	±90°
	Length of gripper	11.1mm
Driving power transfer module	Degrees of freedom	6
Sliding module	Displacement of insertion	144 mm

B. *Phantom design*

For experiment, a sinus phantom is constructed by using the CT data of a patient. The 3D model of the phantom is designed using the 3D slicer software, and the prototype of the phantom is produced by RP machine as shown in Fig. 13. A soft material was employed to simulate the soft wall of the sinus cavity (soft material: Tango Plus).



Phantom design using CT data of a patient(3D Slicer SW) | Prototype of sinus phantom

Figure 13. 3D design and prototype of phantom for experiment.

C. *Experimental Works*

1. *Motion of end-effectors*

Initially, we conducted an experiment to test the performance of the two end-effector modules. Fig. 14 shows the bending motions of the two end-effector modules. The base continuum mechanism of each end-effector module can be bent in two ways (right/left and up/down) maximally up to 180 degrees. Especially, it is noted that the radius of curvature is less than 10mm when the base continuum mechanism is bent to 180 degrees. This is the clinical requirement for inspection of the maxillary sinus area. It is also noted that the distal continuum mechanism of each end-effector module can be bent up to 90 degrees.

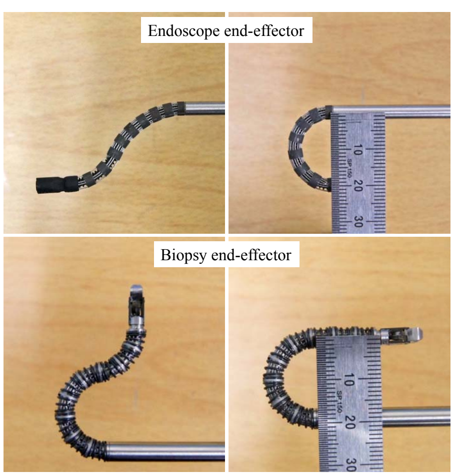


Figure 14. Bending motion and radius of curvature of the two end-effectors.

A bending force experiment for the biopsy device was also carried out. A force/torque sensor is employed to measure the bending force. Fig. 15 shows the experimental apparatus. The result was that the biopsy end-effector module was able to resists the pulling force up to 2.5N, which is favorable in sinus surgery because the tissue biopsy operation does not require much payload.

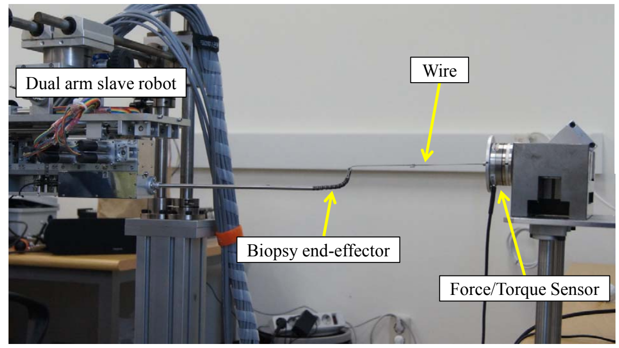


Figure 15. Bending force measurement of the biosy end-effector.

2. *Dual arm operation in maxillary sinus area of a human phantom*

Finally, using the dual master-slave, an experiment for inspection and biopsy in maxillary sinus area was executed. Fig. 16 shows several scenes of inspection through the nasal cavity and biopsy operation at the base of maxillary sinus. Usually, we perform a zigzag operation of the two end-effector modules. The endoscope end-effector module stays behind the biopsy end-effector and provides the scene of the front view of the sinus cavity as well as the position of the biopsy end-effector module. Using this information, the surgeon manipulates the master device to control the insertion motion of the biopsy end-effector module. The attached video clip demonstrates the performance of the dual master-slave system for maxillary sinus surgery, which includes the following information.

(i) Motion of the dual slave robot in the open space

(ii) Comparison between 2 DOF and 4 DOF endoscope mechanisms

(iii) Master-slave dual arm operation in the maxillary sinus area

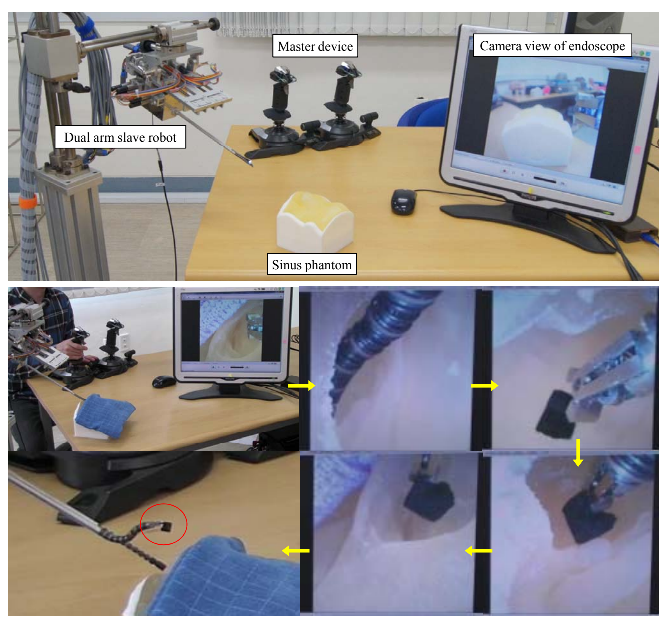


Figure 16. Dual arm operation in maxillary sinus area of phantom using the dual master-slave robotic system.

Fig. 17 shows a micro CMOS camera which provides a view inside the maxillary sinus area. Its diameter is 4mm and a set of light source using a LED is installed around the camera lens. The specification of the CMOS camera is described in Table II.

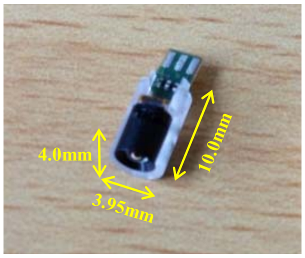


Figure 17. Micro CMOS camera.

TABLE. II. SPECIFICATION OF MICRO CMOS CAMERA

Resolution	400 x 400 pixel
Dimension	3.95 x 4.0 x 8.5
Power input	DC 3.3V
Production Company	Samsung Electro-Mechanics

IV. CONCLUSION

A dual master-slave robotic system for inspection and biopsy in maxillary sinus was developed in this paper. A design to arrange two end-effector modules closely within 1mm was devised to insert them into nostril with small diameter. Necessity of employing 4-DOF endoscope and biopsy mechanisms was explained and a new design for the biopsy device is proposed. A user-friendly dual master device was suggested to control motions of the two end-effector modules inside the nasal cavity. A motion scheduling algorithm switching from the base continuum mechanism to the distal continuum mechanism, or vice versa, of each end-effector module was proposed and tested. Finally, using the dual master-slave robotic system, inspection through the nasal cavity and biopsy operation at the base of maxillary sinus were successfully demonstrated.

As a future work, we plan to incorporate navigation software into the dual arm master-slave robotic system since it enables a surgeon to monitor a target lesion, relevant organs, and the tool position of the robot system in real-time and resultantly improves the operational success rate with safety in the sinus surgery.

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REFERENCES

[1] A. Parmar, D. G. Grant, and P. Loizou, "Robotic surgery in ear nose and throat," *European Archives of Oto-rhino-Laryngology*, vol. 267, no. 4, pp. 625–33, 2010.

[2] J. De Ceulaer, C. De Clercq, and G. R. J. Swennen , "Robotic surgery in oral and maxillofacial, craniofacial and head and neck surgery: A systematic review of the literature," *International Journal of Oral and Maxillofacial Surgery*, vol. 41, no. 11, pp. 1311-24, Nov, 2012.

[3] H. Iro and J. Zenk, "A new device for frontal sinus endoscopy: First clinical report," *Otolaryngology - Head and Neck Surgery*, vol. 125, no. 6, pp. 613–616, Dec. 2001.

[4] K. Bumm, J. Wurm, C. Bohr, J. Zenk, and H. Iro, "New endoscopic instruments for paranasal sinus surgery," *Otolaryngology - Head and Neck Surgery*, vol. 133, no. 3, pp. 444–449, Dec. 2005.

[5] http://www.olympusamerica.com/msg_section/msg_endoscopy_rhinolaryngoscopes.asp

[6] J. Burgner, P. J. Swaney, D. C. Rucker, H. B. Gilbert, S. T. Nill, P. T. Russell III, K. D. Weaver, and R. J. Webster III "A bimanual teleoperated system for endonasal skull base surgery," in *Proc. of IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 2517-2523, 2011.

[7] M. Rilk, D. Kubus, F. M. Wahl, K.W.G. Eichhorn, I. Wagner, F. Bootz, and H. Poor, "Demonstration of a prototype for robot assisted endoscopic sinus surgery," in *Proc. of IEEE Int. Conf. Robot. Autom.*, pp. 1090- 1091, 2010.

[8] E. Y. Hanna, C. Holsinger, F. DeMonte, and M. Kupferman, "Robotic endoscopic surgery of the skull base: a novel surgical approach," *Arch Otolaryngol Head Neck Surg.*, vol. 133, no. 12, pp. 1209-1214, 2007.

[9] H.-S. Yoon, S.-M. Oh, J.-H Jeong, S.-H. Lee, K. Tae, K.-C. Koh, and B.-J. Yi, "Active bending endoscope robot system for navigation through sinus area," in *Proc. of IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 967-972, 2011.

[10] H.-S. Yoon, Y. Choi, and B.-J. Yi, "A 4-DOF bendable endoscope mechanism for single port access surgery," in *IEEE ICRA Workshop: Snake, Worms and Catheters: Continuum and Serpentine Robots for Minimally Invasive Surgery*, pp. 54-56, 2010.

[11] B. A. Jones and I. D. Walker, "Kinematics for multi-section continuum robots," *IEEE Transactions on Robotics*, vol. 22, no. 1, pp. 43-55, 2006.

[12] R. J. Webster III, A. M. Okamura, and N. J. Cowan, "Toward active cannulas: miniature snake-like surgical robots," in *Proc. of IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 2857-2863, 2006.

[13] N. Simaan, R. Taylor, and P. Flint, "A dexterous system for Laryngeal surgery," in *Proc. of IEEE Int. Conf. Robot. Autom.*, pp. 351-357, 2004.

[14] D.-G. Choi, B.-J. Yi, and W.K. Kim, "Design of a spring backbone micro endoscope," in *Proc. of IEEE/RSJ Int. Conf. Intell. Robots Syst.*, pp. 1815-1821, 2007.

[15] H.-S. Yoon and B.-J. Yi, "A 4-DOF flexible continuum robot using a spring backbone," in *Proc. of IEEE Int. Conf. Mechatronics and Automation*, pp. 1249-1254, 2009.