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Endoscopic Camera Control by Head Movements for Thoracic Surgery

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***Abstract*— In current video-assisted thoracic surgery, the endoscopic camera is operated by an assistant of the surgeon, which has several disadvantages. This paper describes a system which enables the surgeon to control the endoscopic camera without the help of an assistant. The system is controlled using head movements, so the surgeon can use his/her hands to operate the instruments. The system is based on a flexible endoscope, which leaves more space for the surgeon to operate his/her instruments compared to a rigid endoscope. The endoscopic image is shown either on a monitor or by means of a head-mounted display. Several trial sessions were performed with an anatomical model. Results indicate that the developed concept may provide a solution to some of the problems currently encountered in video-assisted thoracic surgery. The use of a head-mounted display turned out to be a valuable addition since it ensures the image is always in front of the surgeon's eyes.**

I. INTRODUCTION

Video-Assisted Thoracic Surgery (VATS) is a minimally invasive way to perform cardiac surgeries such as valve repair and atrial fibrillation ablation [1]. The main benefit of minimally invasive surgery is that the trauma for the patient afterwards is relatively low compared to conventional open surgery. In VATS the surgical area is reached by establishing three access ports in the patient's body through which the instruments and a thoracoscope, an endoscopic camera, are inserted.

During VATS a thoracoscope is inserted through the thoracic wall to allow the surgeon to see inside the body. A thoracoscope is a rigid device that needs to be held and steered by hand. This has several disadvantages, which can be classified in two categories. Firstly an assistant is needed to hold the thoracoscope, which requires space in the area where the surgeon has to stand (Fig. 1). This leads to an unnatural cramped position for both the surgeon and the assistant, which can result in fatigue and stress [2], and leads to an unstable endoscope view. Furthermore, as discussed in [3], it is unlikely that the assistant moves the camera in exactly the way the surgeon would like.

Secondly the maneuverability of the thoracoscope is limited. To obtain the required sideway view on the heart region with the rigid thoracoscope, the access port needs to be placed in the side of the chest. The two instrument access ports are also situated in this area. This may cause the instrument motions to interfere with the thoracoscope motion. Maneuverability is also limited due to the thickness of the chest wall and the small distance between the ribs where the thoracoscope has to fit through. Another disadvantage of a rigid thoracoscope is the fulcrum effect that the assistant has to deal with. This means that the movement of a surgical instrument inside the patient is scaled and reversed in direction with respect to the movement outside. This can be counterintuitive for the assistant, and the motion of the instrument outside of the patient may interfere with other instruments.

Fig. 1. **VATS surgery:** The assistant (left) needs to hold the thoracoscope in between the hands of the surgeon (right). This causes an unnatural cramped position for both.

As a solution to the first category of problems several robotic systems that can hold rigid endoscopes have been developed. These systems allow the surgeon to control the movements of the endoscope which reduces the need for an assistant. Examples of such systems are the *AESOP* [4] and the *Freehand* [5]. As a solution for the second category of problems, in recent years semi-rigid endoscopes have been developed [6], [7]. These kind of endoscopes have a rigid part and a flexible part, which enlarges the area inside the body that can be visualized by the camera. They also reduce the motions of the device required outside the patient. One step further is to use a completely flexible endoscope. As discussed in [8], [9], [10] a flexible endoscope such as a bronchoscope or a gastroscope can provide a solution to the maneuverability problems in VATS. An additional advantage is that a large part of the system may be positioned away

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from the patient reducing the required space in the area where the instruments are operated.

However, at the moment there are no systems available which allow a surgeon to control a flexible endoscope by other means than his/her hands. In this paper, we will present a camera control system that enables the surgeon to steer the tip of a flexible endoscope using head movements. This will enable the surgeon to control the camera movement by himself/herself, eliminating the disadvantages associated with an assistant that controls the camera.

The paper is organized as follows: in Section II, the required camera movements for VATS are investigated. Section III describes the control algorithms that are considered to realize these movements by means of head motions. Section IV discusses the design and the realization of the camera control system. The evaluation of the system is discussed in Section V. Section VI concludes and provides possible directions for future work.

II. CAMERA CONTROL FOR VATS

To assess the feasibility of using head movements for camera control, we have studied the camera motions that are performed in VATS surgeries. Based on this, we have defined a system architecture, which will be discussed in this section.

Three VATS mini-maze surgeries were attended in order to gain knowledge about how an endoscope is used during surgery. A mini-maze surgery intends to cure atrial fibrillation, an abnormal heart rhythm. It was observed that the movements of the endoscope can be classified into two categories. The first category are large and rough movements for general inspection purposes such as getting an overview of the thoracic cavity. This is done with the camera fully zoomed out. The second category are relatively slow and accurate movements, when a complex action was performed on a certain spot.

This way of moving the endoscope shows analogies with the way the human motor control system works. As discussed in [11], a head movement consists of a ballistic phase which is a fast movement towards the target and a corrective phase in order to accurately reach the target. This similarity with endoscope movements suggests that these phases can be used for controlling an endoscope view.

Thus, a camera control system for VATS should enable the surgeon to make both small, accurate and larger, less accurate movements. The surgeon should be able to control these movements without using his/her hands. Based on these requirements, we have defined a system as shown in Fig. 2. The surgeon wears a sensor that measures the orientation of his/her head. This information is processed by a control system, that steers the actuators. These actuate the orientation of the tip of a flexible endoscope. The surgeon uses a foot pedal as a clutch to enable the system when he/she wishes to move the camera. A clutch allows the surgeon to disable the system in order to move his head to a natural orientation without moving the camera. Furthermore, it allows extending the camera movement range beyond the movement range of the surgeon's head.

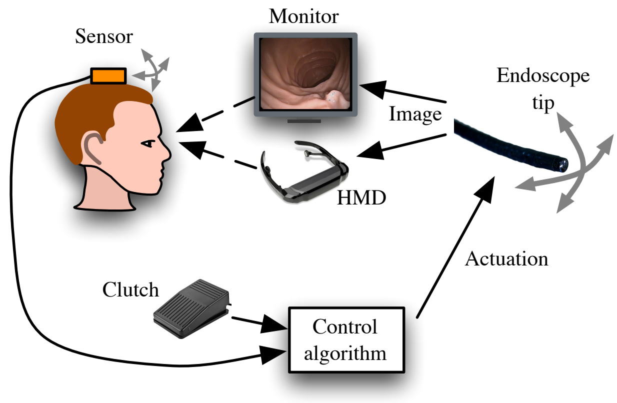

Fig. 2. **System overview:** The surgeon wears a sensor that measures his/her head movements. These are processed by the control algorithm and used to actuate the endoscope tip if the clutch is pressed. The surgeon sees the endoscopic image on a monitor or on a head-mounted display (HMD).

The endoscopic image can be observed on either a monitor or a Head-Mounted Display (HMD). Using an HMD will ensure that the endoscopic image is always in front of the surgeon's eyes, so he/she can move his/her head freely in order to control the camera.

III. CONTROL

In order to get an intuitive behavior of the system, the coupling between the head movements and the camera motion is important. In this section, we will first describe some basic principles of control by head movements found in literature. Subsequently, the three control algorithms that were considered are described.

A. Head movement cursor control

Several studies have been performed on head movements as an input for computer cursor control for people with disabilities [12], [13], [14], [15]. In literature, cursor controllers are often characterized by the control-display (CD) gain. The CD gain describes the relation between the input parameter, for example a velocity, and the corresponding output parameter. In general, two types of CD gain can be distinguished, a constant gain (CG) and a variable gain (VG). In [13], a comparison is made for different values of the CG gain value for head cursor control. A VG is usually dependent on the input velocity: if the user moves slowly, the gain is set low, while a fast movement results in a higher gain. The VG principle is applied in many current devices where a cursor is used. According to [12], the time performance with a computer mouse when using a VG is about 5% faster than a CG. However, no literature about head control with a VG was found.

B. Control algorithms

The three control algorithms were partly derived from the literature about head cursor control [12], [13], [14]. In every controller the pitch movement of the head (looking up

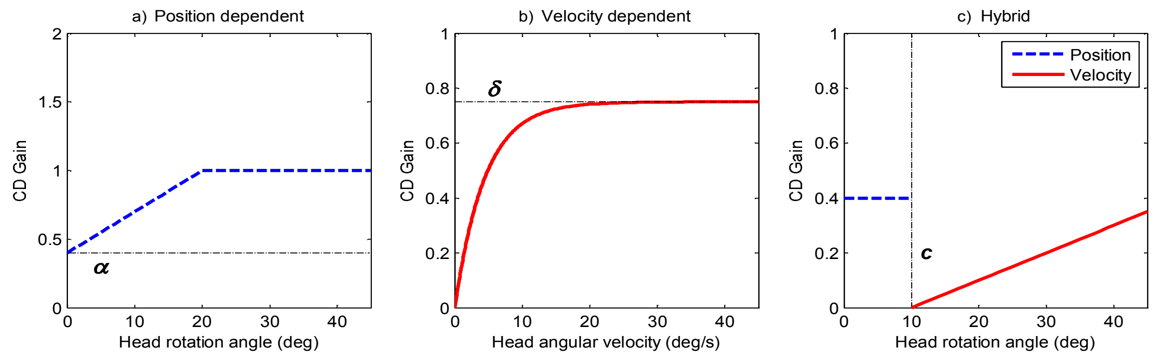

Fig. 3. **CD gain characteristics of the three control algorithms:** (a) In the position dependent algorithm the head position determines the camera position. (b) In the velocity dependent algorithm the camera velocity is coupled to the head velocity. (c) The hybrid algorithm switches from position control to velocity control when the head rotation exceeds threshold **c**.

and down) was used for moving the camera in the vertical direction and the yaw movement (looking left and right) was used for moving the camera in the horizontal direction.

1) Position dependent algorithm: In the position dependent algorithm the angle of the head is related to the position of the camera. Further away from the initial point the gain is increased. The gain is limited to prevent a too low accuracy at the outer range. The algorithm is described by

$$CD = \begin{cases} \alpha + \beta||\mathbf{p}||_2 & 0 < ||\mathbf{p}||_2 \leq b \\ \alpha + b\beta & ||\mathbf{p}||_2 > b \end{cases} , \quad (1)$$

in which α represents the base gain, β the gain increase factor, and b the constant-gain threshold. $\mathbf{p}$ is a vector that represents the yaw and the pitch of the head with respect to the initial point when the clutch was pressed. The CD gain of this algorithm is shown in Fig. 3(a).

2) Velocity dependent algorithm: The second control algorithm uses the angular velocity of the head as input and the output is a velocity. An exponential gain curve is used for achieving the desired sensitivity. It is described by

$$CD = \delta\left(1 - e^{-\epsilon||\dot{\mathbf{p}}||_2}\right) , \quad (2)$$

where $\dot{\mathbf{p}}$ is the time derivative of $\mathbf{p}$, and δ and ϵ represent the gain limit and the gain increase factor, respectively. The velocity dependence of the CD gain results in a large range when fast movements are made and a high accuracy when slow movements are made. The CD gain characteristic of this control algorithm is shown in Fig. 3(b).

3) Hybrid algorithm: The hybrid algorithm uses a constant gain within a specified range c. Outside this range velocity control is applied, which means that a given head angle results in a certain velocity of the camera. This gives the user the possibility to go everywhere by rotating the head beyond threshold c, without the need of using the foot pedal. Every time the pedal is pressed the head angle is defined to be zero. This controller is given as

$$\begin{array}{ll} CD_p = \alpha_2 & 0 < \ ||\mathbf{p}||_2 \leq c \\ CD_v = \gamma\left(||\mathbf{p}||_2 - c\right) & ||\mathbf{p}||_2 > c \end{array} , \quad (3)$$

in which CD_p represents the CD gain with a position output and CD_v represents the CD gain with a velocity output. α_2, γ and c are constants. The CD gain of this algorithm is shown in Fig. 3(c).

The three algorithms were compared in an experiment where 15 subjects (age 18-53, mean age 27) were asked to move a camera in a virtual environment using head movements. The task was to touch certain markers in the environment i.e., move the camera such that a circle in the center of the image overlapped with a marker. The subjects were also asked to fill out a survey in which they gave their opinion on the different algorithms. From the results it was concluded that the velocity dependent algorithm was preferred [16].

IV. DESIGN AND REALIZATION

A commercially available flexible endoscope was chosen as the basis for the camera control system to test the algorithms described in the previous section. An EG2930K gastroscope (Pentax, Tokyo, Japan) was selected (Fig. 4). This gastroscope is normally used for inspecting the upper part of the digestive system. It has a distal flexible part which can be inserted into the mouth, a solid hand part that contains the control wheels and another flexible part that is attached to a video unit and a light source. The tip of the distal flexible part contains a CCD camera that sends a video signal to the vision processor. The tip can be steered in two directions with two wheels that are placed on the hand part. The hand part also contains buttons for controlling air flow through one of the channels or for taking a snapshot of the current camera view. An entrance to a separate channel is located next to the hand part. This channel can be used to introduce various instruments.

A case study was performed on the mechanical properties of five gastroscopes, two from Pentax, two from Olympus, and one from Fujinon. It appeared that for each gastroscope brand the geometry of the hand parts are relatively similar. On the other hand, the shape of the wheels and the positions of the buttons can be considerably different per brand.

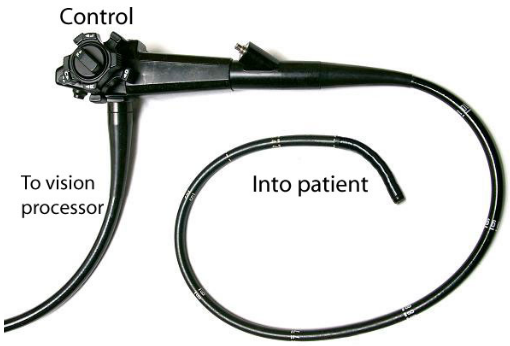

Fig. 4. The Pentax EG-2930K gastroscope was used as the basis for the endoscopic camera control system. The tip is controlled by turning the control wheels.

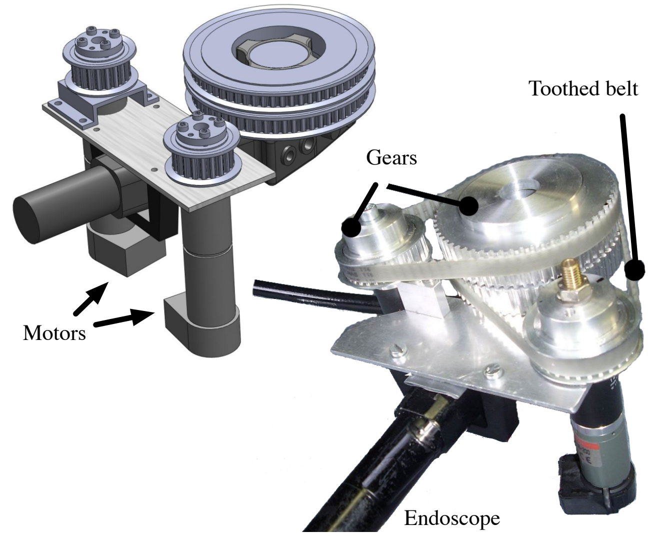

Fig. 5. **CAD drawing (left) and realization (right) of the endoscope actuation:** The gastroscope is clamped using two u-shaped brackets. The large gears are press-fitted onto the gastroscope control wheels. They are driven by the motors via toothed belts.

A. Specifications

The main goal was to control the movement of the gastroscope tip with head movements. The design should be universal so that it can be used with multiple gastroscope brands. In order to keep experiment options open the buttons and the biopsy channel entrance should remain accessible. The design should be small so that almost no space in the working area of the personnel is required. Easy mounting of the actuation system to the gastroscope should be possible. A foot pedal can be used for switching the control on and off, as discussed in section II. Furthermore, the system has to be fast enough so that the user does not experience any delay during usage.

The required tip velocity was based on observations during the three VATS surgeries that were attended. The design specification was set to 15 rpm, so a 90 degree turn of the tip can be completed in one second. Faster movements were considered not useful and can only result in loss of orientation.

B. Design considerations

In order to control the orientation of the gastroscope tip, motors are required to actuate the control wheels. These motors were mounted on the hand part and coupled to the wheels using a toothed belt drive. Since the hand part is similar for different types of endoscopes, this construction can easily be adapted to other types. Because the control wheels of the gastroscope are placed on top of each other, the motors are mounted on different heights (Fig. 5). The larger gears were press-fitted onto the control wheels. For practical reasons concerning available space, the size of the motor gears was chosen as one third of the wheel gears. For fixing the base plate to the hand part of the gastroscope, two u-shaped brackets were used. By placing a material with a high friction coefficient in between, the motors are prevented from moving with respect to the gastroscope.

C. Realization

For the motor selection, torque measurements were performed on the endoscope control wheels at different angles. The maximum torque needed with the large wheel at the end of its movement range was approximately 0.4 N-m. The required velocity is 15 rpm, as defined in section IV-A. Two S2325 motors (Maxon, Sachseln, Switzerland) were selected, which have a nominal speed of 5440 rpm and a nominal torque of 12 mN-m. They were combined with a 76:1 gearhead. Together with the 3:1 reduction of the tooth belt drive, the estimated output at the endoscope wheels, incorporating friction losses, is a maximum of 24 rpm at 1.4 N-m. This is more than the required 0.4 N-m and leaves the option open to use an endoscope that requires a larger torque. An adjustable friction coupling is included on each of the motors to prevent damage to the endoscope when the maximum rotation range is exceeded, for example due to a software error.

Motor control is done with two SimplIQ Whistle motor controllers (Elmo Motion Control, Petach-Tikva, Israel). These are digital servo drives which can be interfaced with the CANOpen protocol. The main program was executed on a computer running Linux. A CANUSB dongle (Lawicel, Tyringe, Sweden) enabled communication with the motor controllers via the USB port. For measuring the head movements an MTi motion sensor (Xsens, Enschede, the Netherlands) was chosen. This sensor measures acceleration, rotational velocity, and the earth's magnetic field, each in all three directions, and uses these measurements to estimate its three-dimensional orientation. The sensor measures $58 \times 58 \times 22$ mm and was fixed on top of a lightweight headband. The total weight of the sensor and the head band is approximately 170g. The sensor was connected to the computer via a USB-RS232 converter. For the foot switch a pedal with a push contact was used, which was connected to a general purpose digital input of one of the motor controllers. A schematic overview of the complete system

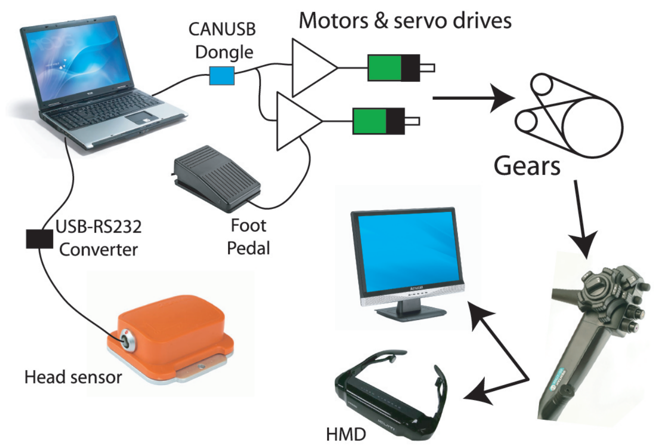

Fig. 6. **Overview of the total system:** The surgeon wears the head sensor on top of the head and is able to see the gastroscope image either on a monitor or on a HMD.

is shown in Fig. 6.

D. Software

The software is written in C++ and makes use of the RS232 and the CANOpen protocols. The main program samples the head sensor input at a rate of 100 Hz and subsequently calculates the required motor output positions. If the foot pedal is not pressed no new position data is sent to the motors. The user has the possibility to stop the program by pressing the 'q' on the keyboard. A flowchart of the main program can be seen in Fig. 7.

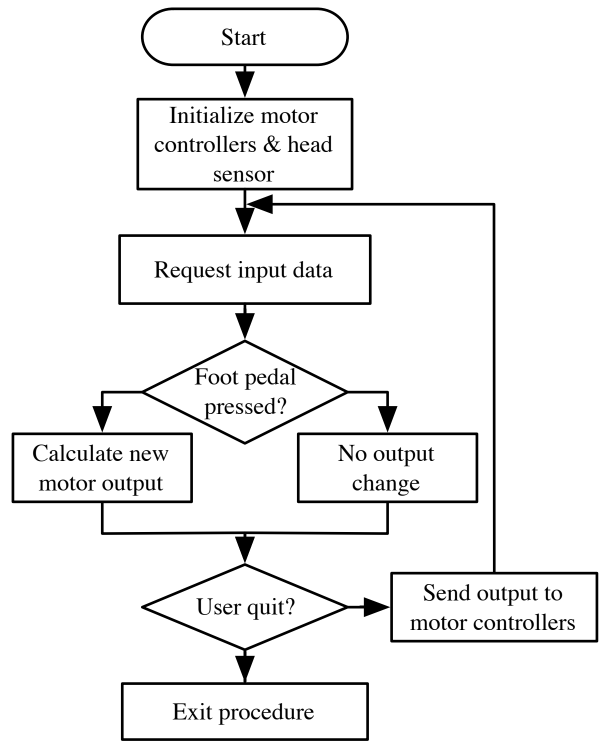

Fig. 7. **Flowchart of the main program:** The inputs of the head motion sensor, the foot pedal, and keyboard are sampled at a rate of 100 Hz.

V. EVALUATION

Several trial sessions with an anatomic model were performed. Because there was no model of the thorax available, a gastroscopy model was used instead (Fig. 8). In the stomach area movements were made to explore the area. Subsequently, several insertion and extraction procedures through the esophagus were performed. The endoscopic view could be seen on a monitor or by means of an HMD (Fig. 9).

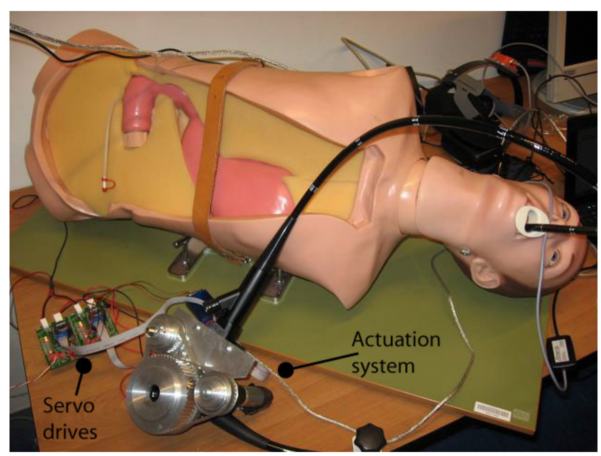

Fig. 8. **Anatomic model on which the trial sessions were performed:** On the front the motors with the gears that actuate the gastroscope control wheels. The flexible part of the gastroscope was inserted into the esophagus.

A. Experiences

Maneuvering through the esophagus and exploring movements in the stomach could be performed with ease. It was found that the pedal was relatively easy to use and required almost no learning time. The setup time of the system was approximately 15 minutes, mainly due to the fixing of the brackets.

When the endoscopic view was observed on the monitor, more clutch actions were needed than when the HMD was used. This was because the subject had to keep looking at the image, which constrained his movement range. This is consistent with the analysis in [16]. The use of the HMD was experienced as a significant advantage because less head movements were needed and the endoscope view was always in front of the eyes. Furthermore, it was observed that more pedal actions were required when vertical movements were made than with horizontal movements. This can be explained by the fact that the human field of view and the neck movement range are larger horizontally than vertically [17].

No delay was noticed between the head movements and the motor movements, and due to the friction in the endoscope the view was very stable. However, is was noticeable that the camera did not move exactly in the same direction as the head motion. This is caused by the kinematics of the gastroscope i.e., the coupling between the pitch and yaw actuation. Compensation for this behavior will be part of future work.

Furthermore, the user has no information about the tip

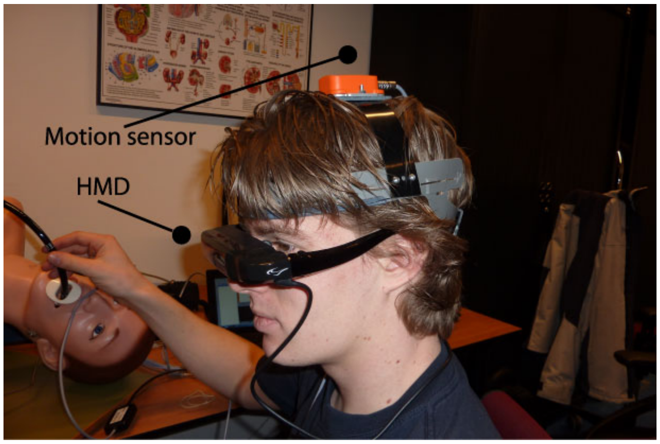

Fig. 9. **Subject wearing an HMD.** The motion sensor that measures the head orientation is worn on top of the head.

orientation and therefore could not know when the tip was not able to turn any further. A visualization of the tip orientation could be provided to the user.

B. Discussion

The setup time of the system is relatively large but can easily be reduced by using another type of connection, where the endoscope snaps into a holder that contains the drive system. Separating the endoscope and the drive system would also make integration in current clinical practice easier.

At the moment only one mode can be selected by continuously pressing the pedal. Other modes like zooming and rotating the video image should also be considered. A possible implementation is to use fast tappings on the pedal for mode switching. One drawback of using a pedal is that since surgeons already have to deal with one or more other pedals during surgery, an extra pedal can cause confusion. Therefore, other options such as voice recognition should be explored. Furthermore, elaborate testing of the derived control structure needs to take place in realistic applications.

VI. CONCLUSIONS AND FUTURE WORK

An endoscopic camera system controlled by head movements has been developed. With this system, experiments can be performed to see whether it is convenient for surgeons to control the camera view of a flexible endoscope by head movements. Trial sessions on an anatomic model suggested that especially in combination with an HMD this concept may provide a good solution to some of the problems currently encountered in VATS. The system can be placed somewhere where it is not in the way for the surgical personnel and also more space is available for the surgeon to maneuver the instruments. For experimental purposes, the system can be easily adapted to fit on different brands of gastroscopes.

More elaborate experiments will be required to get quantitative data on the effectiveness of the system compared to the current practice of VATS. In order to develop a complete robotic endoscope system several functions have to be added to the current system. Especially zooming and rotating are important functions, as these are frequently used during a surgery. Both can be accomplished by digital image processing. A drawback of digital zooming however is that the image quality deteriorates. Another requirement is the addition of a compensation for the coupling between the yaw and pitch motion, caused by the gastroscope kinematics. In a further stage, a software interface that allows manual adjustment of e.g., the sensitivity parameters can be a valuable addition. This would allow the surgeon to adapt the control to his/her personal preference.

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