FPGA and Virtual Reality Based Minimally Invasive Surgery Training System

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Abstract— **The objective of this system is providing an effective tool for junior surgeons to practice and evaluate their fundamental skills and ability of minimally invasive surgery (MIS). In order to achieve these objectives, this system combines the technologies of FPGA and virtual reality (VR) to build a VR based MIS training system. The main function of FPGA is to provide a real time and precise 3D location of instrument. We use DE2-115 FPGA board as the main platform, two D5M cameras as the image sensor in the homemade surgery training box, and the stereo vision technology to get the instrument's 3D location. Then the FPGA platform sends instrument's 3D location to the 3D VR game on the PC in real time by the UART interface. The PC receives the instrument's position from the FPGA and its rotation information measured by the sensor module to control the visual objects in the game. The system can train user's hand-eye coordination and sense of space.**

Keywords— **Minimally invasive surgery; virtual reality; FPGA; surgery training system; stereo vision**

I. Introduction

Since 1805, many surgeons tried inserting the endoscopes into patient's body for replacing the traditional open surgery. Because the surgical wound of minimally invasive surgery (MIS) is much smaller than traditional surgery. As a result, MIS provides patient a better choice to reduce haemorrhaging which costs less pain, smaller incision, and faster recovery [1]. Nowadays, laparoscopic surgery is a kind of popular MIS that the surgeons observe the monitor connecting with endoscope camera to operate instruments in a surgery process.

The surgeons' skills need to improve for achieving the requirement of MIS although MIS has those advantages. Comparing with traditional open surgery, the surgeons only can get the operating information from the monitor and force feedback of instruments, so the binocular vision becomes monocular vision and the 3D vision becomes 2D vision which means the depth feeling is lost. Moreover, the traditional short instruments are difficult to be inserted and controlled in patient's body, therefore, the instruments become slender and need more technique to control it. Due to those changes, the surgeons must possess excellent hand-eye coordination, spatial ability, experience, and skill in MIS.

Appropriate surgical simulation training equipment can improve the learning curve for novice surgeons. Today's simulation training machines generally can be divided into two kinds, the traditional training boxes [2], [3] and virtual simulation training devices [4]-[8]. Box trainer has a simple and cheap benefit, but it only provides basic training courses. The virtual simulation trainer can provide realistic surgical procedure, but the expensive 3D positioning system has become its drawbacks.

Therefore, this paper proposes a low-cost MIS simulation training system. This training system is composed of a surgical training box, the surgical instrument with a sensor module, a stereo vision camera (two D5M camera modules), a DE2-115 FPGA board and a virtual reality (VR) game. The trainees operate the instrument in the surgical training box. The FPGA controls the stereo vision camera to capture the 2D pictures then computing the 2D pictures to get 3D position of instrument. Moreover, the PC converts the 3D position of instrument to control a virtual instrument in the VR game.

II. Methods

Fig. 1 is the system block diagram which can be divided into three blocks including a surgical instrument with a sensor module, a surgical training box embedded the FPGA based image processing unit and a stereo vision camera and a 3D VR game. The image processing unit and sensor module detect seven degrees of freedom (DOF) information of real instruments and transmit to the VR game for controlling the virtual instrument. The seven DOFs indicate the movement, rotation and grasper open/close which are shown in Fig. 2. When moving the instruments, it requires the X, Y and Z position information. The rotation of the instruments is indicated by the roll, pitch and yaw data. Then, to know the grasper situation of instruments, the requirement is the open/close angle. After VR game receiving the seven DOFs data, the animation could fully simulate the real instruments in the VR world. So, more different exercises can be simulated in VR game and junior surgeons can get more practice and training course.

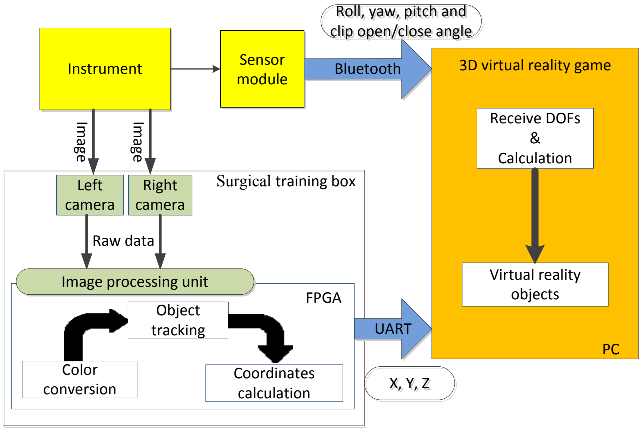

Fig.1. System block diagram.

A. Image processing unit

The Fig.3 is the image processing unit. The main function of FPGA is to provide a real time and precise 3D location of instrument. We use DE2-115 FPGA board [9] as the main platform; the kernel is the Altera Cyclone IV FPGA [10]. FPGA get the raw data of two D5M camera modules and then process the image data for calculating the 3D coordinates of instrument such as X, Y and Z. After the transformation, this system transmits the 3D coordinates to VR game by the UART.

The image processing flow in hardware includes the white balance, color space conversion, marker color detection, dilation, erosion and coordinates calculation. Besides, we use SOPC Builder [11] to integrate the Nios Ⅱ [12] and hardware algorithm for coordinates calibration and modification of white balance and color maker parameter. The result of every step could be output to the LCD screen by setting different switches on the DE2-115.

1) White Balance: Because of different light sources, the object may not be the same read value on sensor. Therefore, we add the white balance processing to improve the color shift effect and display the nature color before color space conversion. It also can increase the noise immunity.

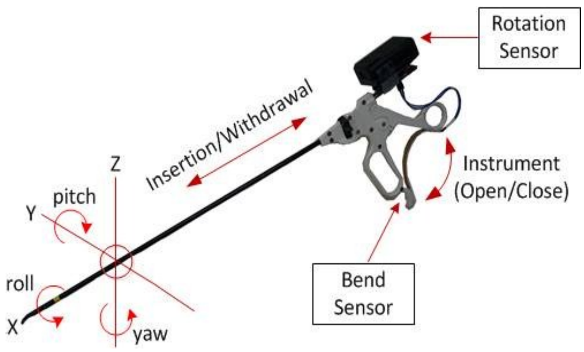

Fig.2. Seven DOFs of the laparoscopic instrument.

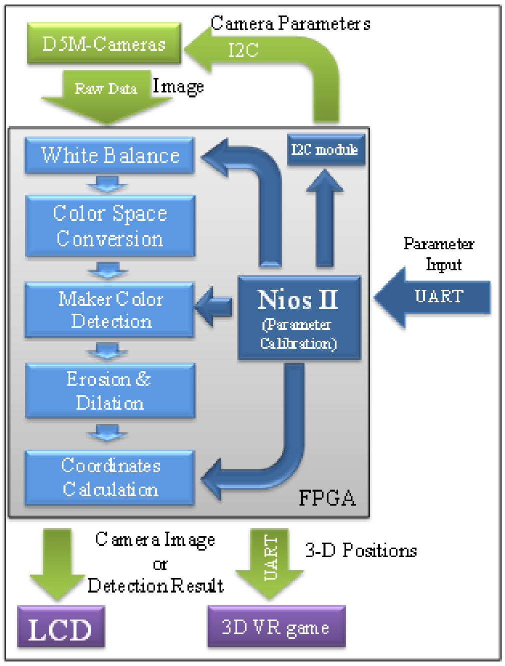

Fig.3. Image processing unit.

In this system, the gain of D5M camera is adjusted to achieve while balance. First, a white paper is placed in the image center, and the system can read the RGB value of that point to adjust the RGB gain of camera according to following conditions:

Definition: Max = max(R, G, B), Min = min(R, G, B), RGB = 0~255

- Adjust the shutter speed till Max = 224
- Max ≠ R，increase R gain till R = 224
- Max ≠ G，increase G gain till R = 224
- Max ≠ B，increase B gain till R = 224

After white balance, it can decrease the color detection error so that the system can get better noise immunity. Fig.4 shows the image before white balance, and Fig.5 shows the one after white balance process. We can see the marker color is yellow.

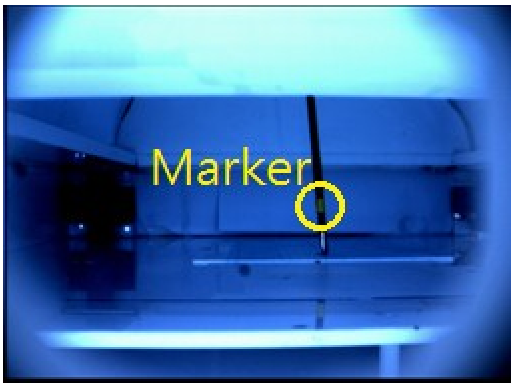

Fig.4. Before white balance.

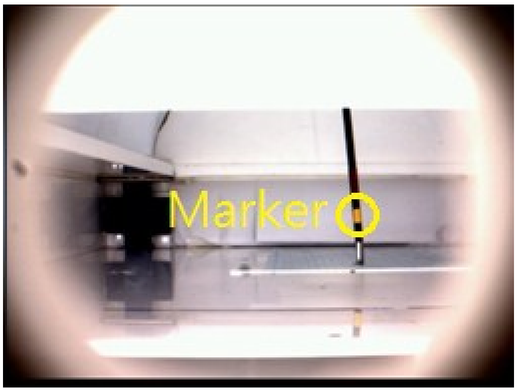

Fig.5. After white balance.

2) Color Space Conversion & Marker Color Detection: A yellow marker as shown in Fig.5 is labelled on the instrument in order to detect the movement position of instrument. The original image raw data output from the camera is RGB format. First, we convert the RGB to HSV model because HSV model is more suitable for color detection. Then, we set a threshold to discriminate the yellow marker. Finally, the marker color detection block outputs a Boolean data maps for erosion and dilation process.

$$H = \begin{cases} 0°, & if\ max = min \\ 60° \times \frac{G-B}{max-min} + 0°, & if\ max = R \text{ and } G \geq B \\ 60° \times \frac{G-B}{max-min} + 360°, & if\ max = R \text{ and } G < B \\ 60° \times \frac{B-R}{max-min} + 120°, & if\ max = G \\ 60° \times \frac{R-G}{max-min} + 240°, & if\ max = B \end{cases} \quad (1)$$

$$S = \begin{cases} 0, & if\ max = 0 \\ \frac{max - min}{max} = 1 - \frac{min}{max}, & otherwise \end{cases} \quad (2)$$

$$V = \max \quad (3)$$

$$Where \begin{cases} max = \max(R, G, B) \\ min = \min(R, G, B) \end{cases}$$

3) Erosion, Dilation and Marker Center Detection: The erosion and dilation block is used to filter the unwanted noise. After the erosion and dilation, we can detect the center of the marker. In our previous study [13], [14], (4) is used to calculated the center of marker. But if the shape of maker in the image becomes irregular and not as a fixed pattern, the calculated center will be biased due to the noise causes coordinates offset uncertain, inaccurate and poor noise immunity. Therefore, the geometric center method (5) is a better choice for getting the marker center more correctly. Fig.6 shows the two marker center detection methods.

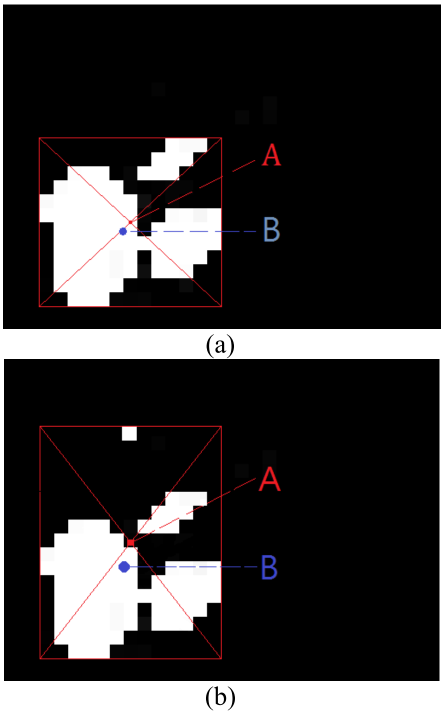

Fig.6. Marker center detection methods.

$$A(x, y) = (\frac{\max(X)) + \min(X)}{2}, \frac{\max(Y) + \min(Y)}{2}) \quad (4)$$

$$B(x, y) = \frac{\sum_{k=1}^{n}(x_k, y_k)}{n} \quad (5)$$

(x_k, y_k) is the pixel which value is non-zero.

4) 2D to 3D Coordinate Transformation: When the marker center is found, we can use the stereo imaging theory geometry to get the 3D coordinate of the marker. Fig.7 shows the simplified stereo imaging system. The formula is shown as following:

$$\frac{X_1 \cdot d_x}{f} = \frac{x - \frac{b}{2}}{z}, \frac{X_2 \cdot d_x}{f} = \frac{x + \frac{b}{2}}{z} \quad (6)$$
$$\frac{Y_1 \cdot d_y}{f} = \frac{Y_2 \cdot d_y}{f} = \frac{y}{z}$$

$$\therefore x = b\frac{(X_1 + X_2)}{2(X_1 - X_2)}, y = b\frac{(Y_1 + Y_2) \cdot d_y}{2(X_1 - X_2) \cdot d_x} \quad (7)$$
$$z = b\frac{f}{(X_1 - X_2) \cdot d_x}$$

Where d_x and d_y are the Camera sensor's pixel to pixel length in X and Y direction. b is the distance between two cameras, f is the focal length.

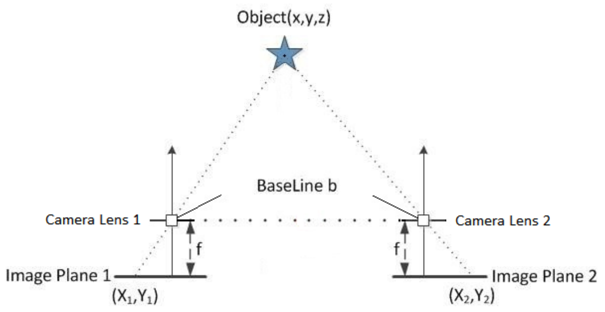

Fig.7. A stereo imaging system.

For calibrating the image distortions caused by lens, the Matlab Calibration Toolbox is used to get the f_x and f_y.

$$x = b\frac{(X_1+X_2)}{2(X_1-X_2)}, \quad y = b\frac{(Y_1+Y_2)\cdot f_x}{(X_1-X_2)\cdot f_y} \qquad (8)$$

$$z = b\frac{f_x}{(X_1-X_2)}$$

Where $f_x = \frac{f}{d_x}$, $f_y = \frac{f}{d_y}$ [15].

5) SOPC Builder & Nios II : This design adds a Nios II core in the system, because there are lots of parameters should be modified dynamically. For example, when the light source changes, the while balance parameter should be changed, too. However, the previous system needs to be re-synthesized and it takes a lot of time and inconvenience. Therefore, a Nios II core is the solution of this problem. Modifying a firmware is much shorter time than re-synthesized and it just take about few seconds. Moreover, the parameters even could be changed during runtime stage by controlling the Nios II. The Table I shows how many parameters can be configured in this system.

TABLE I. Adjustable parameters

Name	**Function**
Shutter Speed	Exposure
Green1 Gain	White balance
Blue Gain	White balance
Red Gain	White balance
Green2 Gain	White balance
Hmax	H range of maker detection
Hmin	
Smax	S range of maker detection
Smin	
Vmax	V range of maker detection
Vmin	

B. Sensor Module of Instrument

The main function of sensor module is providing a real time and precise rotation and clip open/close angle of instrument. Gyro is the sensor for measuring the angular acceleration. The X-IO IMU [16] is used in this system to measure the angular momentum of X, Y and Z directions. Then the rotation amount roll, pitch and yaw are calculated and transmitted to the VR game via Bluetooth.

For detecting the opening and closing angle of the instrument clip. We used a bend sensor which is installed on the handle, shown in Fig.2. The resistance value is changed according to the angle of clip open/close. The resistance value is read by a PIC microcontroller and then sent to the VR game via Bluetooth for providing the angle of clip open/close.

C. Virtual Reality Game

The PC based VR game are developed by C# and Quest3D. Fig.8 shows the design architecture. The C# program receives the sensor data from the sensor module via Bluetooth and the X, Y, Z coordinates of marker from FPGA platform. The sensor data include the virtual instrument's rotation axes such as roll, yaw, pitch and clip open/close angle, the coordinates of X, Y, Z means the virtual instrument's moving axes at the three-dimensional space. Quset3D is the 3D engine for the VR game. In the system, Quset3D program is an embedded "ActiveX control" in the C# program, and the C# program could transmit data by "setChannel" and "getChannel" to control the animation. Therefore, the seven DOFs data are collected by C# and then C# program controls the 3D animation in the Quset3D by "ActiveX control" method. [17]

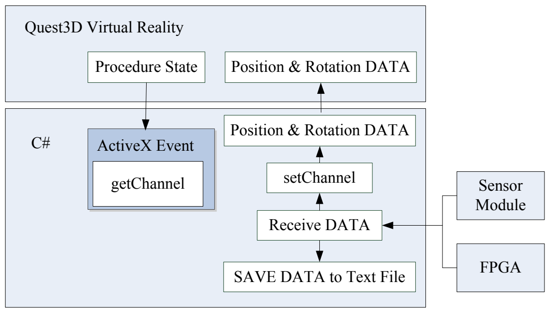

Fig.8. Virtual game design architecture on the PC.

In this paper, we create a VR based ball-grasping module for whole system demonstration. User can operate the real instrument to control the VR instrument in the VR game. Fig. 9 shows the VR game and user interface on the PC. The executing time and scores will be displayed and recorded.

The time is starting counting when the instrument grasps the first ball. Then, the following step is grasping the ball from the left cone into the right hole of cylinder. If a ball is put into the hole correctly, the score will get one point. The training program is ending when all cones are empty and no ball could be grasped. The program's purpose is training the hand-eye coordination of the trainer.

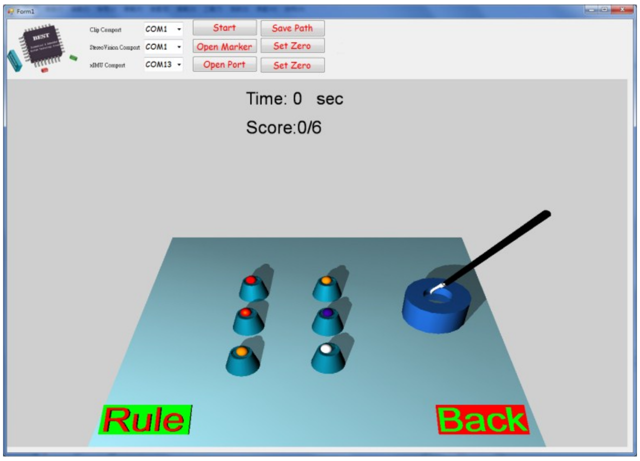

Fig.9. Virtual game and user interface on the PC.

III. Result & Discussion

In this paper, we finished whole system described in above and proposed a new instrument positioning system which can detect the movement, rotation and grasper open/close which are the requirements for a VR based training system. This work fixed the shortcomings of our previous work and integrates with new sensors; there are five changes in this version:

A. Add White Balance

For the movement, we improved our previous design. In the previous design, the system would be interference with different light source due to different color temperature. In this design, a Nios II based auto white balance system is used to improve the effect of light source.

B. Higher Camera Resolution and Frame Rate

Next, this design raises the 320*240 camera resolution to 640*480 which can enhance the accuracy from 0.125cm to 0.0625cm at the 40*30cm vision range. Moreover, the increasing resolution and the increasing data amount do not decreasing the processing speed and the speed is increased to 10~12 FPS (frame/sec).

C. New Sensor Module for Detecting Rotation and Clip Angle of Instrument

For the rotation, an open source sensor X-IO IMU is used to measure the roll, pitch and yaw of instrument in this design. For the clip open/close angle, we designed a sensor module with a bend sensor. When trainer closing and opening of instrument handles would cause the value of bend resistance which is mounted on the instrument has corresponding change. Therefore, the measurement of resistance could get the open/close angle.

D. New Virtual Reality Scenes

Finally, the new VR game provides more realistic and more fun scenes for user to practice the fundamental skills and ability of minimally invasive surgery.

In future research, the wiring method between the camera and FPGA board could be improved to increase the data transmission quality. Then the higher pixel clock of camera could be used. Moreover, the higher resolution and the higher frame rate could improve the detection accuracy and reactive speed. In virtual games part, the simulation of human organs could be added and provide more similar clinical practice. So, the surgical game can guide and teach the novice surgeons more skill and experience.

IV. Conclusion

In this paper, we combined the technologies of FPGA and virtual reality to design and implement an effective tool for junior surgeons to practice and evaluate their fundamental skills and ability of minimally invasive surgery. The prototype of this system is finished and will provide for users to evaluate.

Acknowledgment

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