Low Cost Virtual Reality Laparoscopy Simulator

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Abstract— A low cost solution for virtual reality laparoscopic training is presented in this paper (VRLSS – Virtual Reality Laparoscopic Simulator). The objective of this product is to provide the medical community an affordable low cost solution to train themselves. Even though several simulators are available on the market with high standards and advanced technologies, their use is extremely limited due to the economic costs involved. But the laparoscopic surgery's success is greatly dependent on surgeon's skills and training because Laparoscopy is a surgical procedure in which operations in the abdomen are performed through small incisions using several specialized instruments. This approach ensures that any surgical trainee or medical student can afford a virtual reality laparoscopy trainer to train themselves. The system is easily upgradable and extensible that can provide a wide variety of surgeries and tasks to train with. The developed prototype consists of a set of inexpensive sensors and two webcams. Video image processing and microcontroller based interface have been used as the main technical aspects.

Keywords— Abdominal cavity, Laparoscopy, Simulator, Surgeon Surgery, Virtual reality

I. INTRODUCTION

Laparoscopy surgery is a modern surgical technique that is getting popular among the medical community. Due to the fact that laparoscopy surgery has major advantages over the open surgery like less hospital stay, less recovery time and less probability of infection. Therefore, patients and surgeons favor laparoscopy surgery [1]. Laparoscopy surgery is performed using a special instrument and the laparoscope is inserted into the abdominal cavity through small incisions (usually between 0.005 and 0.015 m) made on the skin. Laparoscope is a camera attached to a thin metal telescope to watch a magnified view of the inside of the abdomen on operating room monitors [2]. The long, thin instruments are used to perform various tasks like dissecting and suturing. A sharp-pointed surgical instrument fitted with a tube called a trocar is used to insert these surgical instruments into the abdominal cavity. The instruments are put through the tube. This access port enables the surgeon to take out one instrument and put another one with ease.

The success of the laparoscopic surgery greatly depends on the surgeon's skills and training. Box trainer, animal model and virtual reality trainer can be identified as some of the popular training methods in the current context [3].

In a typical box trainer, a box is used to imitate the abdominal cavity, the instruments inserted into it and a camera placed inside the box to provide the view on the monitor. This method is a globally accepted and a proved method. The products that use this concept are even available in the market [4]. But the tasks are restricted in this method and they have failed challenges of recreating the environment of the abdominal cavity and the ability to restore the environment to perform the same surgery again. The perfect training model should teach the skills required and should be inexpensive, universally available, and anatomically and physiologically identical to an anesthetized patient [5]. The box trainer teaches the skills, but it is not identical anatomically with patients.

In that method an animal or human cadaver is used to simulate and train surgeries. Not every animal can be used for this since the anatomy of every animal is not identical with the human anatomy. The most commonly used animal is pig due to the similarities with its anatomy with the human anatomy. But there are issues like unavailability and cost. The effectiveness can be questioned because the sizes of the organs are different in two species. This solution is not a take-home solution. The training sessions are held as workshops and because of that trainees do not get an opportunity to train as much as they need. Another issue with this method is that using animals for surgical training is not promoted nowadays. Animal welfare organizations are against using live animals for surgical training. But this method is still used under protests and abided by laws that are enforced for the betterment of animals.

The virtual reality training method is the solution for all the drawbacks in the other methods. In virtual reality training the surgical environment is created using 3-D graphics. All the internal organs and surgical instruments are made as 3-D objects. Virtual Reality training has been proved popular in aviation throughout the decades and effectiveness of virtual reality simulation for training in laparoscopic surgery already [6]. This is a computer generated simulation that provides the exact view inside the abdominal cavity. Since the trainees should get the real feeling of performing the surgery, a typical virtual reality simulator comes with real laparoscopic grasper handles. There is nothing lacking in a virtual reality simulator compared to the real laparoscopic system. When compared with the other alternative methods for laparoscopic training, the virtual reality method has some added advantages. It provides a performance feedback to the user indicating successful the tasks or the surgery was. This grading and assessment feature is an added advantage for the user and can be trained alone and improve their performances [7]. It is also considered as an effective training method that can be customized and upgraded to train a wide variety of surgeries and tasks. But existing virtual reality laparoscopic trainers are not affordable due to their costs. This paper presents a prototype that provides a solution to that issue to make the virtual reality simulation a perfect ideal training method for all the surgical trainees all over the world.
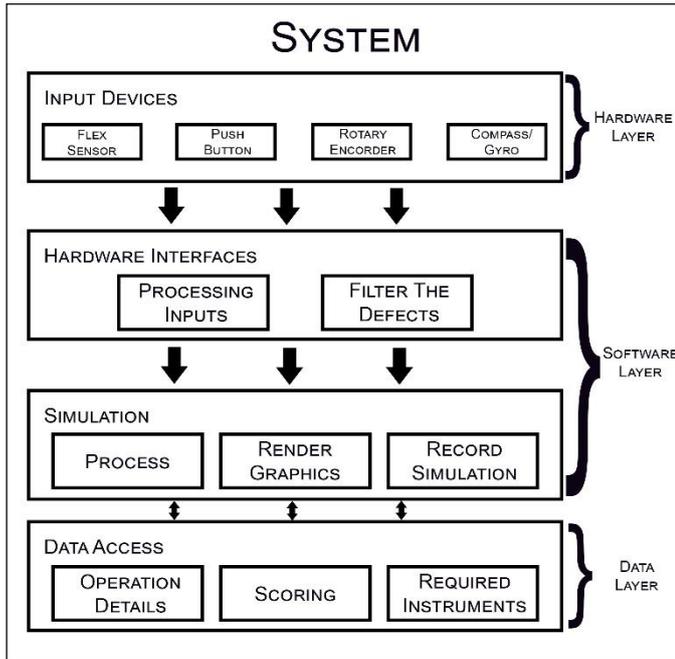
II. METHODOLOGY

A. Requirement

Fig. 1. System Overview

1) Functional requirements: During the actual surgical procedure the surgeon controls the instruments from the grasper handles. The tips of the instruments differ according to the tasks. As an example a scissor contains a scissor at the tip of the instrument. The movement of the tip is required to be captured to project it to the virtual environment. This tip can be rotated using the rotational knob in the gasper handle. This rotation is also needed to be captured to rotate the virtually created instrument tip. And if the instrument contains two blades like a scissor the opening and closing is controlled by the gasper handle. This open/close situation is also needed to be captured as it plays a vital role in performing the surgery. The laparoscopic system consists of a foot switch to provide cut and coagulate instructions separately to the diathermy unit. It is an essential feature in a laparoscopy system because the blood vessels are needed to be coagulated if necessary when performing the surgery. The tissues are cut not just by force. The diathermy unit assists this task by providing heat to the tip of the instrument. Apart from these basic essential requirements that are needed for the trainer to function properly, there are other requirements that were identified to make this a low cost solution. As shown in the Fig. 1 the system can be divided into three layers called hardware, software and data. The hardware layer consists of the four sensors and the cameras that capture the inputs from the instruments. A console application that has been written using the C# programming language processes and filters these inputs before writing them into two separate files

as a file per each grasper. These data are used by the unity 3D engine to create the simulation and control the objects in the simulation environment. Two cameras operate independently in this architecture since they are using OpenCV object tracking algorithm to generate the coordinates in the three dimensional space. The data layer of the system is responsible for storing the data that is needed for the simulator to be operational as well as the performances of the users.

2) Other Requirements: PC "Plug and Play" feature enables the solution to be a low cost one. Rather than having dedicated peripherals or processing, if the simulator can be connected to the personal computer or the laptop that belongs to the user it can reduce the cost from a considerable amount.

User report generation is an important feature since it enhances the effectiveness of the device. Since VRLSS is presented as a take-home solution, the users can be trained wherever and whenever they need. But normally the training is done under the supervision of a senior surgeon. The user report generation feature provides a feedback on the performances highlighting what went wrong with a complete assessment based on completion time and mistakes committed. The users will have the privilege of accessing their previous performances to check whether they have gained any improvements. Information is presented in a user friendly manner with the aid of graphs.

B. Hardware Solution

Two real laparoscopic instruments are allowed in the simulator for the user to provide a real experience. Precisely grasper handles are connected to a metal rod in the simulator. Since this is a virtual reality solution, the projection has been done using 3D graphics. Therefore the actual tip is not needed. As mentioned in the functional requirements there are some inputs that are required to be captured. The developed prototype consists of a set of inexpensive sensors, namely as flex sensor, a rotary encode switch and push buttons. There is a linear relationship between the handle opening and the forceps at the tip of the instrument [8]. This relationship is used by the flex sensor. The rotary encoder switch captures the rotation of the tip when the rotational knob of the instrument is rotated. This sensor is ideal to read the position of the rotational knob since it has the freedom to be rotated 360°infinitely to both the ways clockwise and counter clockwise. The rotary encoder switch has 5 pins as 3 pins for the rotary encoder and 2 pins for the push button. This push button is not used to capture any input in the simulator. The 3 pins can be identified as common (ground), high and low. An Interrupt based method is used to read the inputs from the rotary encoder switch because the rotary encoder switch is not constantly generating inputs. When a user rotates only the rotational knob, the switch generates inputs. Another reason to choose the interrupts based method is that it brings less overhead to the microcontroller compared to the polling mechanism. Flex sensor is an analog sensor which changes in resistance depending on the amount of bend on the sensor. Inside the flex sensor there are carbon resistive elements

within a thin flexible substrate. When the substrate is bent it produces a resistance output relative to the bend radius. There are two graspers and each grasper carries a flex sensor and a rotary encoder switch. The Push buttons are used in the foot switch of the diathermy unit it capture coagulate or cut instructions.
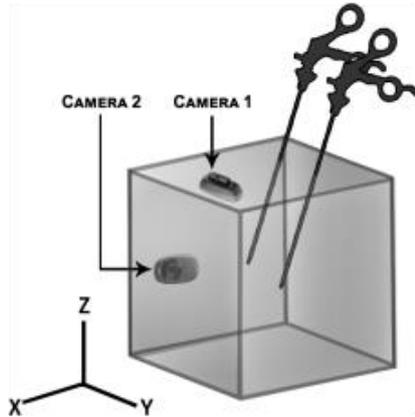

Fig. 2. Schematic view of VRLSS

The movements of the tips are captured with two webcams placed inside of the physical trainer. Minimum of two cameras are needed to detect three dimensions (X, Y, and Z). There should be a camera to capture the X and Y coordinates and another camera to capture Z coordinates. These three dimensions are needed to position the tip of the instrument in the virtual environment.

As shown in Fig. 2 one camera is mounted on the top of the box to capture the X and Y coordinates and the other camera is fixed in the front wall of the box with respect to the graspers to capture the Z coordinate. The box itself is not having any prearranged coordinate system. Those coordinates are generated with the aid of an OpenCV object tracking algorithm. Fig.3 shows the more details of the algorithm behind this object tracking system.

C. Data Acquisition and Communication

There are two data acquisition methods used in the device.

1. Image processing based data acquisition.

2. Microcontroller based data acquisition.

An OpenCV object tracking algorithm is used for the image processing based data acquisition. Two cameras are placed perpendicular to each other. These cameras provide a real time video of what is happening inside the box. Fig. 3 shows the algorithm behind detecting the instrument's tips inside the box. HSV (Hue, Saturation, and Value) values are predefined by using HSV value detection software developed as a part of the project [9].
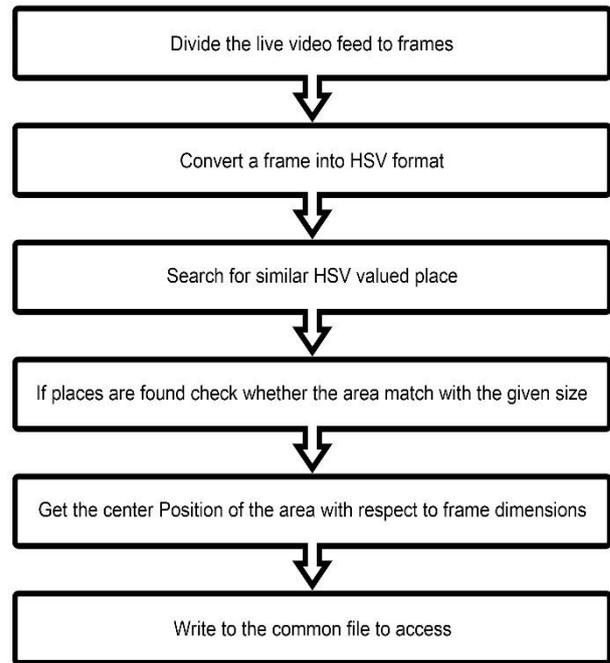

Fig. 3. OpenCV Object Tracking Algorithm

Since there are no real instruments inside the box tips of the metal rods are identified as the tips of the instruments. They are assigned with a color coded and each grasper is detected according to the color. Different object detection methods are used for different purposes in OpenCV. In this research color based object recognition is used to avoid complications as it suits the circumstances. From the two cameras placed inside the box the top Camera is responsible to provide X, Y coordinates and Side Camera is responsible to provide the Z coordinate of the instrument. The accuracy and the validity of using two cameras to capture the movements of the instrument tips have already been proven [8]. There is a coordinate for every position inside the box. Once the image is captured by the cameras it is mapped to this coordinate system to get the 3D position. Both the cameras must be functional for the simulator to be operated.

Serial Communication Medium is used to connect Arduino microcontroller and CPU, which executes the simulation. The Arduino is responsible to capture the inputs from the sensors while the CPU handles the processing. Even though the sensors provide raw analogue signals, the program which is loaded into the Arduino board converts them into meaningful data. As an example the rotary encoder switch provides +1 and -1 according to the direction it is rotated. The flex sensor provides values from -100 to +100 according to the direction and the degrees it is flexed. There are two states for the push button as on and off. Prototyping stage solution need four USB ports to do the communication in a parallel way, but this can be optimized to two USB ports in future.
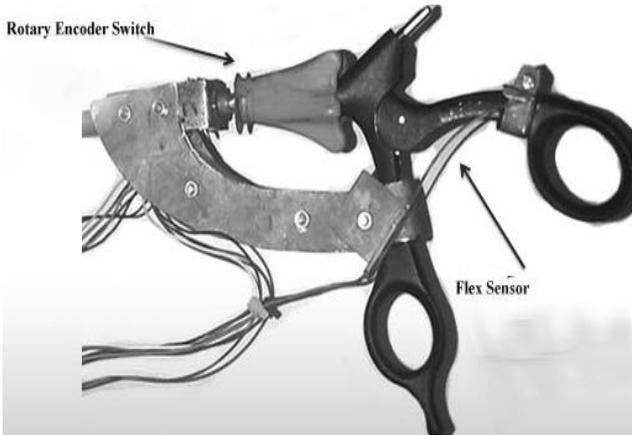
Fig. 4. Sensors Placement

Fig. 4 shows the sensor placement of the grasper handle. There are two types of grasper handles called ratchet and non-ratchet. The ratcheted grasper handles come with a lock that allows the user to lock the instrument tip. The above figure shows an image of a non-ratchet grasper. The rotary encoder switch is connected with the rotational knob of the grasper handle and a flex sensor is fixed in-between the two arms of the handle. There are six sensors and these sensors need to operate parally because some of the tasks are performed together. In the real scenario the diathermy unit is used while cutting a tissue. In simulation environment the flex sensor and the push button should provide readings parallel. Since the data is transferred through one serial port, the Unity 3D software does not have the capability to process them parally. Therefore C# Parallel console applications are used to overcome this issue. Those applications write data separately to files concurrently. Unity3D scripting API access this data in Simulation runtime to make the changes in real time in the simulation environment.

III. RESULTS AND DISCUSSION

Movements of the instruments are restricted to a box of one $0.3048m^3$. Therefore the X axis of the instrument tip is confined to a range of 0 to 1280 pixels, y axis is 0 to 720 pixels and z axis is 0 to 720 pixels. A formula is used to map these readings (input) to the simulation development environment (output). Suppose that $C_{x,y,z}$ is a point in real-world coordinates (x, y, z) and $S_{x,y,z}$ is the coordinate considered in the simulation projection.

$$S_{X,Y,Z} = \frac{(C_{x,y,z} - in\ min) * (out\ Max - out\ min)}{(in\ Max - in\ min) + out\ min} \quad (1)$$

Maximum voltage output reading from flex sensor associated with maximum forceps opening and minimum voltage output reading from flex sensor associated with forceps closing is acquired before starting the training procedure. This calibration procedure is carried out to reduce the errors that can cause by the flex sensor. The rotary encoder switch does not need any calibration. Simply it will generate pulses according to the direction and amount the switch head is rotated.

The prototype was tested in different environments and since the tip is placed inside a box, there is no confusion for the cameras when detecting them. The tips are uniquely identified

according to the color code. Flex sensor and the rotary encoder switch are not sensitive to the magnetic fields and metal. They were thoroughly tested under different conditions.

Since the product was developed with the guidance of the medical community latency was identified as a considerable error in the current system. Sensors and the cameras are having a latency that can be hardly captured by the naked eye. Distortion of the cameras is a major issue that can affect the accuracy of the simulation. However, an accuracy of about 0.003m or 0.004m is accepted for the surgical instrument movement analysis [10]. Rotary encoder switch and the flex sensor were tested and the rotary encoder switch had no issues as its movements are restricted to clockwise and anti-clockwise. It is also fixed to the structure to gain stability. But the flex sensor can be subjected to additional errors due to its high sensitivity and the flexing nature. Even though the preliminary results are very promising and the correlation between the real and virtual movements were in the level of acceptance further tests are needed using different environments and wider range of movements to obtain more precise, concrete and consistent conclusions about the product.

20 surgeons and trainees were assessed using VRLSS in a series of experiments at the initial phase to assess the validity of the system and to evaluate whether practicing VRLSS basic skills (transferring) would result in skill acquisition transferable to complex laparoscopic tasks. The initial task was to reach different depth points using the instruments. This is one of the basic things that surgeons need to practice. In this task trainees are asked to touch four points and the time spent for each point is saved to evaluate the skills.

Validity was confirmed byh using laparoscopic surgeons. For this evaluation, four sphere objects are placed on the simulation environment in different depths as shown in Fig.5.VRLSS. Scores increased progressively with the laparoscopic experience, and residents followed over time practicing improved their scores, and evidences of construct validity. Even at the first time, experienced surgeons spend minimum time to touch a location while first time users take too long to touch one point. To validate VRLSS training module we divide the testing sample into three groups, experienced, Intermediate and trainees as more detailed in Table.1.

Table I. Experiment Sample Details

Groups	Number of Users
Experienced	2
Intermediate	5
Trainees	13

Fig. 5. Simulation Environment – Basic Task

Fig. 6. Average Total Time Spend

Fig. 7. Average Total Time Multiple Attempts
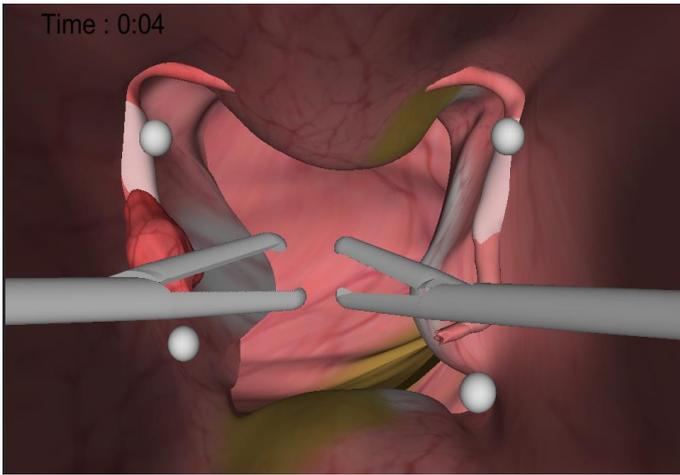
After doing the same task 5 times, users show some progress. Fig.6 illustrates the average total time spending on the entire task and user group. Experienced Surgeons show very minor progress while both Intermediate and trainees have shown a considerable progress. This is clearly stated in Fig.7.

These test results prove that there is a valid training opportunity for the users and they can increase their performance gradually. These test results also prove that experienced surgeons also feel that the simulation environment is somewhat similar to the real surgical environment. Because of this similar feeling, they are the category which spend a minimum time for completion. The accuracy of this testing can be increased with the number of test samples. Furthermore this validation study can be expanded into more tasks available in the VRLSS like cutting and grabbing to prove their validity as well.

IV. CONCLUSIONS

This system provides a simple, low cost laparoscopic trainer with easily upgradable features. The system comes with the plug and play feature to make the system user friendly. Even though the initial development comes with a gynecologic surgery, the future works involve developing a wide variety of surgeries for the user to select and train. Future works involve adding various surgeries for the system. A web based approach will be ideal to upgrade and add new training modules to the system. This "Pay as you go" concept also reduces the cost of the system. Number of USB ports can be optimized easily up to two and the future works involve reducing it up to one or wireless. Haptic feedback will be another concern for the future works. Despite the fact that currently available laparoscopic simulators are expensive, they are fully occupied with advanced features. But the intention here is to provide the medical community with a low cost solution and to let all the surgical trainees train with a virtual reality simulator for the betterment of the medical community as well as the public health.

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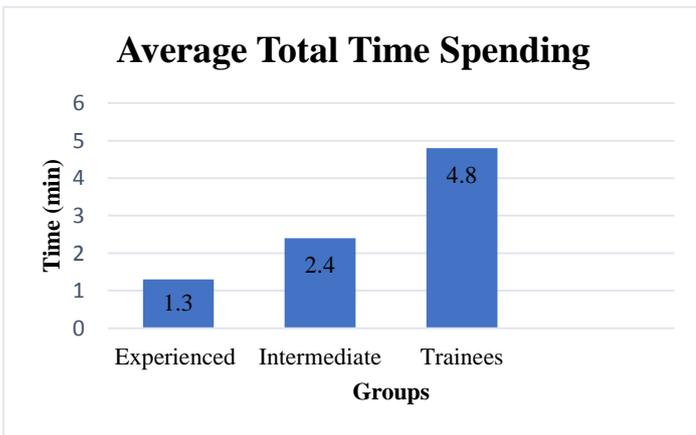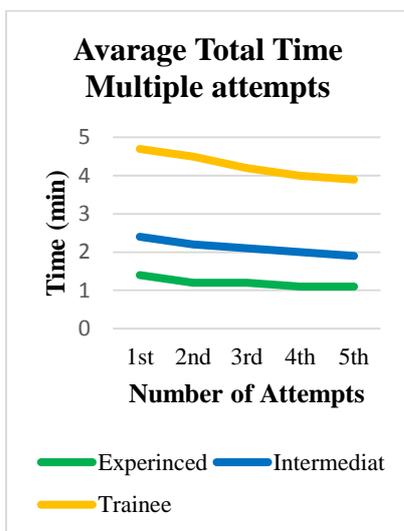
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