Technical Note

Operation and Human Clinical Trials of RoboLens: an Assistant Robot for Laparoscopic Surgery

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ABSTRACT

Purpose- In this report, technical operation of "RoboLens" as an assistant robot for laparoscopic surgery has been illustrated.

Methods- First, the RoboLens® mechanical mechanism and configuration of its linkage, joints and actuators are illustrated. Then, the software and user interfaces of the robot are introduced. Next, its operation from start to end of a surgery has been evaluated. Also, a technical test for its trajectory tracking in a spherical coordinate has been performed using a standard optical tracking system. Finally, an overall report from more than 1000 human clinical trials in 2 hospitals is investigated.

Results- The robot was prepared for the operation in less than 30 Sec and started all the commanded movements including up, down, right, left, zoom-in or zoom-out of the screen in real time manner with less than 50 ms delay. Also, the trajectory tracking of the robot end effector on a spherical surface showed less than 1 mm error in the worst case.

Conclusion- Results of the evaluation of the RoboLens indicated that it has the appropriate maneuvering capability as a robotic assistant for laparoscopic surgery in real human clinical trials.

1. Introduction

Through the past decades, the use of Minimally Invasive Surgeries (MIS) has increased exponentially; and laparoscopic surgery, a branch of MIS in which endoscopic instruments are used to perform surgery on intra-abdominal organs through small incisions, is rapidly displaced laparotomy, most importantly, because of the lower infection risk, decreased blood loss, lesser pain and shorter recovery period after the surgery [1, 2].

As both hands of a surgeon are occupied with instruments during the laparoscopic surgery procedure, an assistant usually holds the laparoscope and is responsible for providing the surgeon with a clear view of the patients' internal organ and laparoscopic instruments. The assistant should keep the instruments inside the camera's field of view, in order to reduce unintended collisions. This tedious task requires

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constant concentration and can be both tiresome and exhausting, particularly during long duration surgeries. Moreover, it requires high coordination between assistant and surgeon, as the assistant should follow surgeon's commands while not limiting his/her workspace. The fulcrum effect makes this process even harder, since the assistant's movements contribute to a reversed and scaled motion in camera's output [3, 4].

Efforts have been made in order to resolve the above-mentioned issues and facilitate the laparoscopic surgery procedure by employing robotic assistants [5-13]; but only a few of these systems have been evaluated clinically [14-20]. Using robotic assistants for camera manipulation not only reduces the number of staff in an operating room and therefore expands the workspace of the surgeon, but also can decrease the surgeon's fatigue and surgery's duration by providing the surgeon with direct control over the camera orientation [21].

In this study, the capability of RoboLens® (Sina Robotics and Medical Innovators Co. Ltd., Tehran, Iran) as a robotic laparoscopic surgery assistant to providing the surgeon with the necessary control over laparoscopic lens will be investigated.

2. Materials and Methods

2.1. Robot Mechanism

During the laparoscopic surgery, the laparoscope camera must enter the abdominal cavity through a small incision on the abdominal wall. Hence, the lateral movement of the instrument is not possible and the available degrees of freedom are reduced to four. Three of these DOFs are rotational in a spherical space while the remaining one is the translational displacement along the insertion axis. Pitch and yaw, two of the rotational degrees of freedom, determine how much the laparoscope is inclined to the left, right, up or down, while the last DOF describes the rotation of the instrument around its longitudinal axis.

RoboLens uses a low cost mechanism that can control the aforementioned degrees of freedom, previously done by surgeon's assistant effectively (Figure 1). Its mechanism uses a serial configuration of a single linear and two orthogonal rotary actuators as well as a passive rotary joint. Both of the rotating motors are placed on the head of the robot and they are attached by a rigid horizontal arm to the vertically-aligned linear actuator located at the top of RoboLens base. Therefore, the head of the robot can be placed over the incision point and above the surgeon.

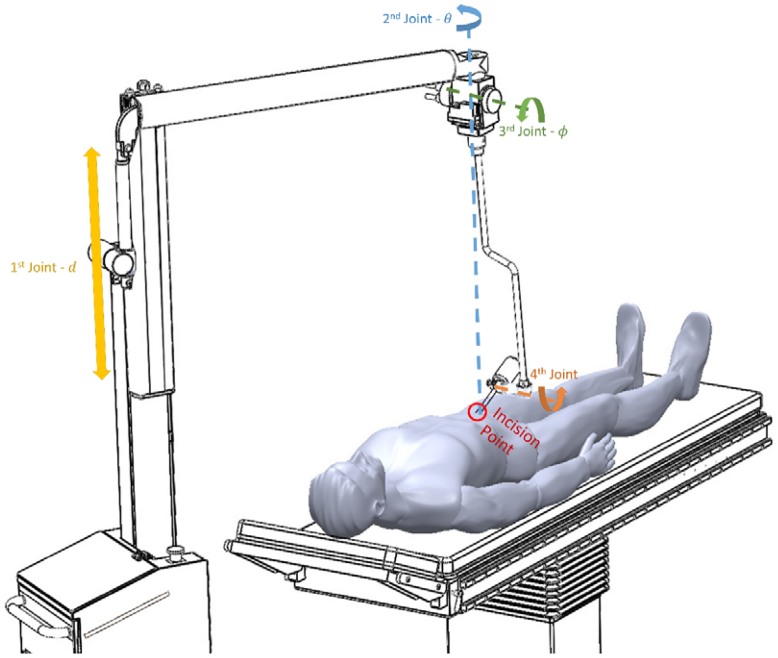

Figure 1. RoboLens mechanism and its degrees of freedom. The first joint is prismatic while the rest are rotary. Also, except the last joint, all others are actuated.

Rotary motors, located at the head of the robot, are connected to a thin detachable rod that can hold the laparoscope with a rotatable wrist. The center of the motion of mechanism, located on the intersection point of the first rotary motor's axis of rotation and longitudinal axis of endoscope, should coincide with the incision point; ergo, a laser pointer marks the axis of rotation of the first rotary actuator. This will allow the operator to identify the proper positioning for robot by pointing the laser tower incision point.

To maximize the robot's mobility, the base of RoboLens is installed on a cart. Therefore, it can be moved to a convenient position on the patient's bedside and ensure the center of motion is exactly located on the incision point. Also, there is a central locking mechanism for base wheels to keep the robot fixed during the operation procedure.

The first rotary actuator (in Figure 1) allows the robot to rotate the laparoscope to left or right around the incision point. The combination of the second rotary (in Figure 1) and linear actuator (in Figure 1) makes the up and downward movement around the incision point possible. This combination also allows the zoom-in and zoom-out operations by moving the laparoscope along its longitudinal axis. During the above-mentioned motions, the laparoscope will not rotate around its longitudinal axis; ergo, the orientation of view will not change. However, this rotation can be applied manually during the operation, for instance, in case of using angulated lens.

2.2. User Interfaces

Since one of the main aims for developing a robotic cameraman was to eliminate the need for the presence of an assistant during the operation, and as both hands of the surgeon are occupied during the surgery procedure, the user interface of the RoboLens was of paramount importance. Three different hands-free controlling systems were used as the user interfaces of the RoboLens.

The first user interface system is a smart 6-button footswitch (Figure 2. a). The foot switch is consisted of two pedals. The right pedal is used to control the lateral movement of the camera (up, down, left and right) while the pedal located on the left side of the footswitch allows the surgeon to control the zoom in and zoom out operations. Upon the activation of the footswitch by the surgeon, the robot starts accelerating steadily in the appropriate direction until reaching a certain maximum velocity that could be set before the start of the operation. By releasing the pedal, the speed decreases to zero in less than 0.5 seconds. In any circumstances, for safety reason and prevention of any continuing movements in case of mechanical failure of the pedals, movement of the robot will be terminated after 6 seconds. The pedal status is checked by the software at 1000 Hz.

The second interface system is a voice command system. It requires the surgeon to wear a headset. A single button footswitch is also used to facilitate the hands-free commanding interface. By pushing the button on the aforementioned single-button footswitch and then saying one of the "up", "down", "right", "left", "in" or "out" words, the software will process the surgeon's command and will repeat it in the headphones of surgeon to ensure the command is properly recognized (Figure 2. b). By continuing to push the pedal, the surgeon will signal the validity of the recognized command and the robot will move in the corresponding direction until releasing of the pedal.

As a safety measure, both footswitch and voice control systems will not work continuously for more than 6 seconds and to continue the movement, the surgeon should release and re-push the smart pedal.

The third user interface is an autonomous and marker less instrument tracking system. The RoboLens central processor uses a novel marker-free segmentation algorithm in HSV color space to identify the tip of the surgical instruments in the output video of laparoscope camera in real-time. Then, the RoboLens will move the laparoscope stem such that the Instrument's tip remains at the center of the video output. Therefore, the surgeon can dedicate his/her focus on the procedure completely and the computer will automatically control the laparoscopic images (Figure 2. c).

Since the program should detect the tip of instrument in real-time and then move the RoboLens accordingly, the instrument tracking algorithm is implemented in a parallel processing scheme. The first processing thread captures a single frame of the video output of laparoscope and detects the tip of instrument before sending the coordination to the next thread. The second thread uses the tip position; sent by the first thread and the robot current configuration; specified by the third thread, to generate the appropriate commands for the RoboLens' actuators [22].

A smart surgery shoes with ability to recognize the surgeon foot movements using its optical sensors is another user interface of the RoboLens (Figure 2. d). Using this UI, surgeon may control the intra abdominal view, via his/her foot movements on the ground. In this system, moving the right foot to front, rear, left and right; commands the robot to move the laparoscopic lens, up, down, left and right respectively. Also moving the left foot to front and rear commands the robot to zoom in and out.

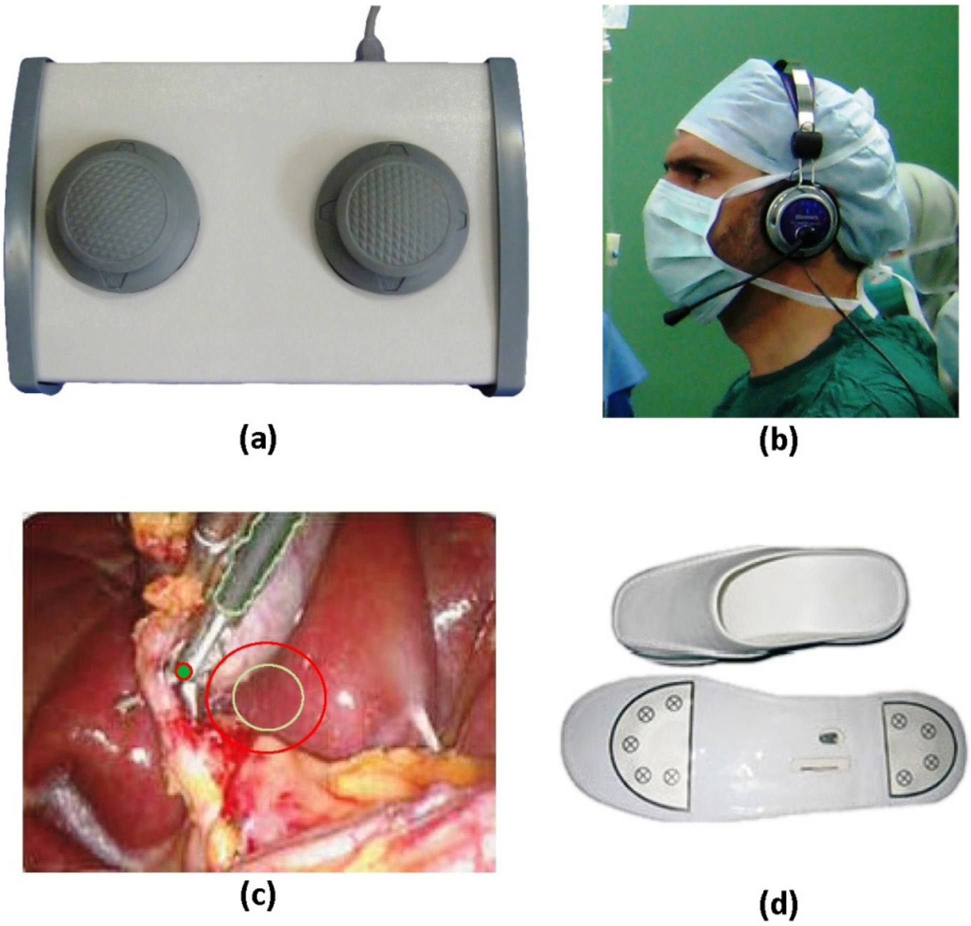

Figure 2. User Interfaces of the RoboLens to control the laparoscopic view: (a) Six button footswitch, (b) voice commands, (c) smart instrument tracking system using a marker free image processing method, (d) smart surgery shoes to track the surgeon's feet movements and control the laparoscopic view.

The RoboLens also has a friendly Graphical User Interface (GUI) to set up the robot before operations (Figure 3). The operator can interact with the robot through the touch screen display that is installed on the upper part of the robots' base. The main page of GUI allows the operator to choose the maximum velocity of movements, turn the laser that is used to put the center of motion on the incision point on or off and signal the start of operation. Before the start of the surgery, the surgeon can select the desired control method from the GUI's main page and the interface allows the operator to switch between these control methods.

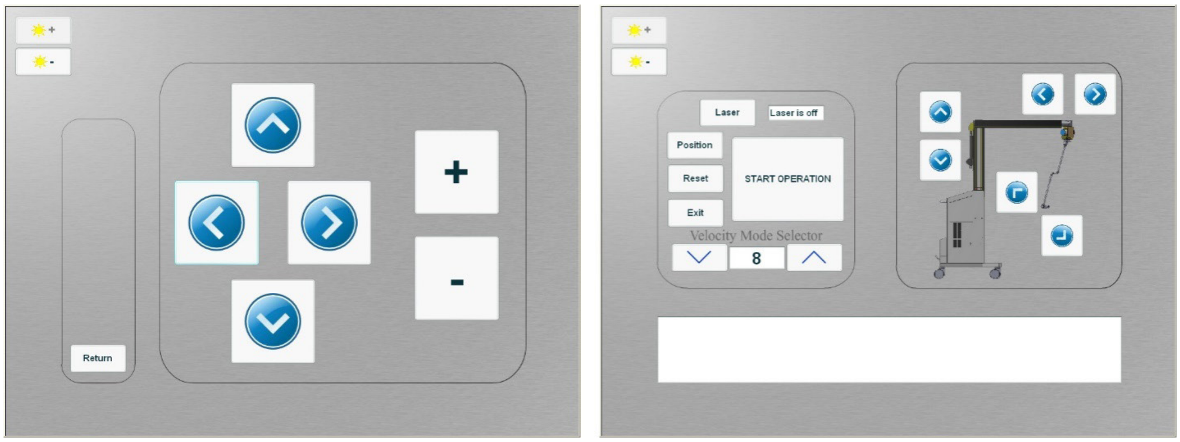

Figure 3. Graphical User Interface of the RoboLens. Configuration page is visible on the right side; the operator can adjust the basic setting before starting the operation. Left picture is the interface during the operation. This allows the user to control the laparoscope camera orientation directly using touch screen.

2.3. Experimental Evaluation

Moving the robot end effector on a spherical surface around the incision point is the main need for a laparoscopic camera holder robot. To evaluate the capability of the RoboLens regarding this need, the Micron Trackers real-time stereoscopic vision system (Claron Technology Inc., Ontario, Canada) is used as a real time 3D trajectory tracking system. It is synchronized with the RoboLens commanding software and the time delay in starting the movements and any error from the desired spherical surface are investigated.

As a commercially available robot, RoboLens is used in 4 hospitals in Tehran, Iran. It has the Iran Medical Devices ministration certificate and this study was performed in accordance with the declaration of Helsinki and subsequent revisions and approved by the ethics committee of Tehran University of Medical Sciences. In this study, an overall report of its operations at real operating room is investigated.

3. Results

The investigation on 3D trajectory tracking of RoboLens did not show more than 1 mm deviation error from the spherical surface around the incision point. The Robot operates very smoothly and in a real-time manner. The maximum delay between commanding and starting of a movement is less than 50 ms.

Regarding the clinical human trials, the reports show more than 1000 surgeries using RoboLens V1.1 and V2.2 during the last decades. Figure 4 shows the latest version of RoboLens (version 2.2) at an operating room. The clinical studies on laparoscopic ovarian cystectomy surgeries done with the assistance of RoboLens revealed that although using the robotic cameraman will require a longer setup time comparing to its human counterpart (5.9 minutes on average), it can greatly reduce the total surgery time (from more than 100 minutes to less than 70 on average). More importantly, the use of RoboLens led to less surgeon fatigue and fewer number of camera head cleanings [23].

Figure 4. Operational configuration of RoboLens V2.2 at operating room.

4. Discussion

In this report, the main features of RoboLens, a robotic cameraman for laparoscopic surgeries, were investigated. The mechanism of robot is effective since the system uses the minimum number of actuated degrees of freedom required for manipulating the camera during the laparoscopic surgery. This was achieved by using an unactuated rotary wrist at the most distal joint of robot, which not only prevents the camera from rotating along its stem axis and distorting the output video, but also can safeguard the objects in case of unintended collision with the laparoscope.

Although the velocity profiles are generated with a small oscillating error because of vibration of robot's arm, there are imperceptible to naked eye and the total movement of the video camera are smooth and accurate [24].

As the vertical arm positions the head of robot above the surgeon's height and on top of patient's body, the robot will not interfere with the view of surgeon and the maneuver limitation would be minimum [23].

The horizontal arm of the robotic cameraman, which is movable using the linear actuator, can rotate and sit next to the vertical arm above the base of the RoboLens. This retraction mechanism and the fact that the robot is installed on four wheels increases RoboLens' portability, particularly during the time between surgeries and when the robot should be moved between the operating rooms. The reason is when the horizontal arm is retracted to the vertical position and the linear actuators move both arms to lowest possible point, the height of the robot decreases dramatically and the robot can easily move in and out of the ORs, even those with a small entrance. The handle that can facilitate these movements is installed on the upper part of the base just below the display. The locks that can be used to restrict the movements during surgeries, is located on the lower part of the base and bellow the mentioned handle.

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