Image Guided Robotic Assisted Surgical Training System using LabVIEW and CompactRIO

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Using LabVIEW and CompactRIO with FPGA to develop a real time robotic simulation platform for advanced laparoscopic surgical training system.

The Challenge

To design and implement a 5 DoF robotic platform with deterministic motion control and tracking, which allows real time interaction with Virtual Reality medical objects for advanced laparoscopic surgical simulation.

The Solution

We used LabVIEW to develop the control and communication modules of the robotic platform, with the CompactRIO for real time motion tracking. To efficiently control the 5 DoF motion of the manipulator, the FPGA in the CompactRIO is programmed for the high-frequency motion control.

Introduction

Laparoscopic surgery is widely applied for disease treatment due to the advantages of small incision, fast recovery, less infection etc. As an example, about 95\% of cholecystectomies are performed laparoscopically in the United States \cite{1}. It is a safe procedure only when it is performed by properly trained surgeons \cite{2}. We are developing a new generation of laparoscopic surgery training system that incorporates master surgeons’ surgical experience into the training process to provide realistic training environment and an accurate motion control for the robotic arms. It helps to shorten the young surgeons’ learning curve for such surgeries. In our system, the LabVIEW, with a user friendly interface, is used as the primary system development platform. Together with CompactRIO and embedded FPGA it ensures fast development and prototyping.

Solution for advanced laparoscopic training

One conventional approach in surgical training is through the ‘master-apprentice’ and ‘hand over hand’ strategy. It is a time consuming procedure for master surgeons to accompany with all trainees. With technology development, surgical simulators have been used widely for self learning/training. However, those simulators do not embedded with the expertise of experienced surgeons. In order to provide a solution to the problem, we developed a robotic assisted laparoscopic training system, which mimics the real operating environment by training in a collaborative manner through robotic active guidance method.

The entire system consists of two main parts. One is the surgical simulation in virtual environment. The other is the robotic platform for active motion guidance. Fig. 1 shows a structure of the surgical training system. LabVIEW, LabVIEW FPGA and compactRIO are chosen as the development environment for the robotic platform.

Laparoscopic surgical instrument is constrained to five degrees of freedom during a typical surgical procedure, namely pitch, yaw, roll, translation, and handle grasping motion. To implement such a 5 DoF manipulator, we designed a hybrid spherical mechanics for the rotational motion, with rack and pinion for the linear motion, and modified surgical handle for grasping motion. The two manipulators of 5 DoF robots is shown in Fig. 2. A rod with modified surgical handle that serves as Human Machine Interface (HMI) is equipped to simulate the surgical instrument.
Fig. 1 Structure of surgical training system. (a) Robotic device for laparoscopic surgical training. (b) Virtual simulation. User operates on the robotic assisted surgical instruments, which guide the virtual instruments in the interaction with the virtual anatomical model. The CompactRIO works as motion controller to move the instruments with compensation to friction forces, provide haptic feedback, record the trajectories of surgical instruments and provide active guidance for trainees. The CompactRIO FPGA is programmed to for fast motion control and motion sampling.

Fig. 2 (a) Robotic device with two manipulators of 5 DOF controlled through CompactRIO. (b) GUI for motion control visualization.

**Hardware system**

The primary hardware development platform is based on LabVIEW while the main motion control is implemented using CompactRIO, with Xilinx Virtex-5 LX110 reconfigurable I/O FPGA core and a real time embedded controller with 400MHz processor, 128 MB DRAM memory, and NI9205, NI9403 NI9505 and NI9235 module. Each of the robotic manipulator is installed with high precision force sensing unit, ATI Nano17, calibrated at forces resolution of 0.0125N and torques resolution 0.0625Nmm. Fig. 3 shows the architecture of the control scheme.
One of the key challenges in an active robotic system is to actuate the motion and force control in a high sampling rate to ensure the motion and haptic fidelity. By adopting CompactRIO FPGA based real time hardware platform, the control of the manipulator can be implemented at 20k Hz in the robot platform to ensure the task determinism and motion fidelity in our simulation. Using FPGA allows minimal delay in the compensation of the parasitic forces. The parallelism nature of the FPGA operation also facilitates the fast and robust coordination among the axes of the robot. The control operation and computational task is hard coded using LabVIEW FPGA. LabVIEW FPGA provides a high level description/abstraction and an easy interface for the fast prototyping.

Software system

The hardware development platform is based on LabVIEW and the virtual simulation is implemented with QT, a cross platform application and UI framework, and PhysX engine, a GPU based graphics system. To make the laparoscopic training more interesting and challenging, we proposed system architecture with a training scenario construction and selection components for user to learn the surgical skills with scenarios in different training difficulties. Interactive medical object segmentation and model reconstruction methods are developed for rapid and fast model generation for our surgical simulation [4,5]. The tool tissue interaction is implemented by PhysX, using a multi-layer mass-spring model [3].

The robot communicates with the virtual simulation through a PC UDP port. By receiving motion displacement of the surgical tool from robot, the PhysX based graphics engine is able to simulate the organ deformation and provide tool tissue interaction as a feedback to the robot for haptic display. The API provided in LabVIEW shortens integration efforts of the robot and PhysX engine.

Implementation

The robot has three working modes - initialization, recording and guidance mode. The actuator driven by PWM (Pulse Width Modulation) works under either velocity, position or current control depending on the function of the robot. Fig. 4 shows the implementation of an actuator on pitch axis. In initialization, all motors are working under velocity control. Each motor drives the robot at prescribed speed for initialization in five axes in sequence. Limit switch and NI9403 checks the limit position of the mechanism.

In the normal operating/recording mode, the robot works under current control. Master surgeon interacts with the robot to operate on the virtual anatomical model, and force sensing unit measures the force that the user applied. The parasitic force generated from the system was measured by force sensor and converted into torque on each joint with Jacobian matrix. Each actuator is commanded with appropriate current to move in the corresponding direction according to the direction and magnitude of the torque, and hence reduces parasitic forces.

Fig. 5 illustrates the force compensation control scheme implemented on the system. In addition to force feedback mechanism, a dynamic model can be incorporated to compensate undesirable disturbance. CompactRIO FPGA with NI9235 and 9205 are dedicated to the acquisition and signal processing to achieve feedback response at high sampling rate. The control implementation facilitates the execution of feedback at a rate of $10^7$ Hz to ensure determinism and maintain fidelity. Hence a feedback mechanism is sufficient for the force compensation application.
Fig. 4 Actuator can be optioned to work under velocity, position, or current control. Calculation of current set point is not shown in this diagram.

Fig. 5 Impedance control with force feedback. In the case of parasitic force compensation without tissue interaction, \( F_{res} \) is set as zero. Similar method is applied to generate haptic feedback during tool-tissue interaction in the virtual environment with \( F_{res} \) being the required output of haptic force. \( J_E \) is the Jacobian matrix.

The data logging is an important feature of the robot in recording mode. Position, velocity and acceleration data are recorded on hard disk. Although velocity and acceleration can be obtained by post data processing, they are all calculated at FPGA level and logged separately to allow immediate replay. Since the logged data is going to be reused for active guidance purpose, the data need to be logged at high frequency to ensure motion smoothness when it is executed. The LabVIEW function “queue” is applied in our implementation. All of the data are written in to a queue, and flushed from the queue periodically and written into a binary file on hard disk. Each bundle of data flushed from the “queue” is written as a cluster of arrays. By using the “queue” function, time consumption to access hard disk is greatly reduced, which ensures deterministic running of recording loop. Fig.6 shows the data logging function. This function also facilitates fast data retrieving.

For guidance mode, the surgical tool is autonomously moved as the trajectory recorded previously. Motion is implemented by PID position control. A trainee can hold on to the surgical tool handle to follow the operation. This guidance method could provide the trainee with deeper appreciation of how an experienced surgeon deals with specific surgical scenarios. Fig.7 illustrates the data retrieving and position control. In each loop only one cluster of arrays from each logging file are read and sent for execution. By doing so, the CompactRIO only needs to allocate a small amount of memory to contain the data in each cluster instead of the entire logged data. It ensures that the robot is capable to replay a long trajectory.

There are two manipulators in this robot as shown in Fig. 2. Synchronization of time crucial events is communicated through digital I/O port by NI9403. For example, recording and retrieving data for two manipulators shall be started at same time. Digital I/O ports are used to communicate the trigger of such event between two manipulators. The maximum delay induced by this method can be reduced to as low as two micro seconds.
Fig. 6 Using “queue” for data logging.

Fig. 7 Data retrieving and replaying for robotic guidance.

Experiment and Results

To validate the control accuracy, experiments were performed to acquire and replay the motion trajectory of the surgical tool. Kinematic trajectories were acquired through the encoder with joint control scheme at frequency of 100 Hz and subsequently transformed to 3D Cartesian coordinate. The maximum errors of execution on the left and right manipulators were 2.12 mm and 1.55 mm respectively when there was no interaction during replay of an acquired trajectory. Illustrated in Fig.8 is a visual comparison for one trajectory, which shows accurate motion control implemented.
Fig. 8 Acquired and executed trajectory. Red line is acquired trajectory, and black line is the executed trajectory during guidance mode. The two trajectories are aligned with each other closely.

Conclusion

The contribution of this work is on the introduction of a robot platform implemented using NI LabVIEW and CompactRIO for advanced laparoscopic surgical training. The intuitive LabVIEW development environment provides easy programming facilities, especially working with LabVIEW FPGA to program the CompactRIO with embedded FPGA. It reduces the development and prototyping time significantly.

The image guided robotic assisted surgical training system funded by A*STAR BEP programmes aims to provide surgical skill training with new laparoscopic training platform. An intermediate evaluation for students using the robotic platform shows skill improvement [6]. Besides surgical training, such a system may also be further developed for pre-surgical planning and practice.

The robot is developed with guidance capability to teach the trainees for laparoscopic surgery. This guidance method could provide a trainee with deeper appreciation of how an experienced surgeon deals with specific surgical scenarios. Currently, we are also developing a second version of the robot platform with enhanced haptic feedback for tool-organ interaction, robotic assisted guidance and new virtual anatomical models.

Reference