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ABSTRACT

With the novel advances in wireless communication and personal mobile handheld devices, a newly emerging technology of medical visualization on mobile handheld is believed to provide advance service for physicians, especially in image-based diagnosis. In this paper, we have implemented a real time easy-to-use 3D volume visualization system on mobile handheld devices. The doctors could use their wireless handheld devices, such as Pocket PC or PDA, interactively access medical image at anytime and anywhere in the hospital building. System architecture, technical problems and solutions are discussed. Experimental results are clear enough to show this system to be practical for clinic diagnosis. The transmission rate for lossless compressed 256×256 24 bits color images could reach up to 5 frames per second under 802.11b WLAN standard. With progressive and lossy image compression, the frame rate can be further increased.

Keywords: Medical imaging visualization, mobile handheld device, wireless transmission, image compression

1. INTRODUCTION

Interactive visualization is one of the most important means for the investigation of tomographic data from CT (Computed Tomography) and MR (Magnetic Resonance) scanners.[1–3] The visualization of 3D volume rendering provides the medical staff with extremely important information for diagnosis, especially by showing patient's interior structure. The user can rotate the image, look through it by dissolving away opaque material, take advantage of motion cues and lighting. Since typically the medical volume datasets are enormous, comprising data values at points throughout three dimensional space, they are usually visualized on powerful desktop or laptop through hardware-accelerated rendering or highly optimized software. Conventional visualization system is composed of high-end workstation server and desktop PC client connected by high-speed wired network. Volume data are stored on high-end server, volume rendering can be done on either server or client, and the rendered images are displayed at client. However, since the client is mounted in a fixed location with wired-network connection, doctors are restricted to stay at the same place to use visualization system. With the rapid development of wireless communication and digital device, wireless handheld devices, such as Pocket PC and PDA (Personal Digital Assistant), are becoming more and more widely used. With the

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benefit of increased network bandwidth and processing power, the need for easy-to-use medical image visualization on personal mobile devices is growing. The doctors could interactively access and display volume images on their Pocket PC at any time and from anywhere in the building, so they do not have to stay in a truly fixed terminal location. The easy-to-use visualization system provides them very convenient way in image-based diagnosis of their patients.

Related work includes some remote image visualization systems and telemedicine systems.[1–6] S. Pavlopoulos proposed a outdoor telemedicine system based on wireless communication for emergent service on ambulance.[1] The biosignals, such as ECG signal, blood pressure and heart rate, are sent to expert physicians through GSM mobile telephony network. So the patients could get treatment as early as possible, which is critical for emergency case survival. The important advantage of wireless transmission through mobile telephony network is that mobile telephone service covers a much large area. The telemedicine system can work at any place within the service area. S. C. Voskarides *et al* proposed a remote visualization system via GSM or GPRS cell phone data service.[6] However, the transmission rate is low. The data transmission rate for GSM is 9.6-43.3k bps, and for GPRS is 171.2k bps. Transmitting 256×256 8 bits gray image need 12-53 seconds through GSM and 3 seconds through GPRS. Low transmission speed limits its practical application, especially in real-time medial image visualization system. R. Andrade *et al* built a indoor interactive visualization system of DICOM data through wireless LAN using mobile wireless devices.[2] They use PDA as client to access DICOM data with WLAN 802.11b standard. However, their system is based on a web interface using Internet Explorer. Due to the retransmission structure in TCP/IP, the transmission rate will decrease fast when channel BER is high. Also the web interface is difficult to provide flexible interaction between client and server.

In this project, we are exploring easy-to-use medical visualization system on mobile handheld through WLAN. The valid transmission range for WLAN is several hundred feet, which is sufficient for the indoor application, since the doctors are usually working within a hospital building. For the in-building WLAN, IEEE 802.11 are so far the most widely used standards that specify an interface between a wireless client and a base station. Among them, IEEE 802.11b is the most widely used. Its radios transmit at 2.4 GHz and send data up to 11 Mbps. The actual throughput is about 4 Mbps. The amendment, IEEE 802.11g, raises the data rate to 54 Mbps. Both work at 2.4G Hz. The IEEE 802.11a standard works at 5 GHz, and has a 54 Mbps transmission rate. However, The latest Pocket PC only integrates 802.11b. Integrating 802.11g or *a* needs expansion card, which brings additional weight in use. Table 1 shows some PDAs' specifications on processor, display, and wireless LAN. In our system, newest Compaq iPAC 5500 with integrated 802.11b wireless card serve as prototype client.

For our wireless visualization system on mobile Pocket PC, the challenges of this project are: (1) wireless devices have resource limitations, such as slow processor, limited memory and screen size; (2) comparing to high-speed wired network, the bandwidth of wireless channel is low, while medical volume data sets are huge; (3) image data are easy to corrupt during wireless transmission based on the fading, shading, multipath of wireless channel. The image data need to be robustly protected for channel impairments.

The technical problems involve: How to distribute the visualization task onto client and server? How to trade off compression complexity with limited processing power for Pocket PC? How to choose channel protection scheme, FEC or ARQ? For the solutions of those technical problems, we moved most visualization task to high-end server machine; a fast and simple lossless image compression[7,8] is employed to achieve best trade-off between compression efficiency and computational complexity; we adopted FEC scheme on the UDP socket transport to combat packet loss in wireless transmission.

Table 1. Selected PDAs' specifications on processor, display, and wireless LAN

PDAs	Processor	Resolution	Color Depth	Wireless LAN
iPAC5550	Intel XScale 400MHz	240×320	16bit	Bluetooth, 802.11b
Dell X3	Intel XScale 400MHz	240×320	16bit	Bluetooth, 802.11b
ViewSonic V36	Intel XScale 300MHz	240×320	16bit	Optional
Toshiba E755	Intel PXA255 400MHz	240×320	16bit	802.11b
ASUS A620	Intel PXA255 400MHz	240×320	16bit	802.11b

Preliminary experimental results show the system can achieve good performance under the restriction of limited wireless channel bandwidth and resource of wireless device.

2. EASY-TO-USE MOBILE VISUALIZATION SYSTEM

2.1. General Architecture

Data sets from medical imaging are growing fast. For example, data volume from 3D medical imaging like CT are approaching $512 \times 512 \times 512$ which amounts to more than 100 million of voxel cells. Meanwhile, the gap in computation power between high-end server and low-end Pocket PC client is huge. To get best overall performance, first we need to distribute the visualization task onto client and server. High-end server always have special features that enable them to visualize large volume data sets faster and with better image quality than Pocket PC. Special features of high-end graphics machine are trying to handle such huge data sets by relocating visualization tasks directly into hardware. In our application, we use VolPro 1000 card to render volume data. The algorithm is implemented in hardware on the VolPro board. It can render $512 \times 512 \times 512$ at 30 frames per second and provide real time perspective projection. Pocket PC has no special hardware to accelerate the rendering because of its compact size. In order to exploit the processing power of the Pocket PC efficiently, we move rendering task to server side. Visualization takes place at server side using VolPro board. Server generates and transmits rendered images to Pocket PC. Pocket PC used only as interaction editor. It displays images received from server and allows user to interactively manipulate the visualization parameters, such as the rotation, zoom, pan, and transfer function. Visualization parameters are then sent to the server to generate new rendered images.

The outputs of VolPro 1000 are of high-resolution content-rich images. They are 512×512 in RGBA format, which is much beyond the constraints of transmission bandwidth, processing power and screen size of a typical Pocket PC. To meet the appliance constraints, content adaptation is designed to reduce the resolution of the images to meet the resource limitation of Pocket PC and bandwidth. Content adaptation can takes place at the server side or the client side. In client-side adaptation, the required content adaptation is performed in the client device using device capabilities and client needs. While performing content adaptation in the client is advantageous because the client has intimate knowledge of the current needs and capabilities. This approach requires a large amount of the client's computational resource. In contrast, for server-side adaptation, information about the content is readily available. Furthermore, the rich capability of the server's computational resource may be adequate for dealing with high complexity of the content adaptation process. However, this approach may not have full accessibility of necessary information about the mobile appliance status. In this project, we adopt client assisted server-side adaptation. At the beginning of the visualization, the client reports its capabilities, such as screen size, color depth. The server executes content adaptation to meet client's requirements. The server can subsample volume data or rendered image data. Rendered image

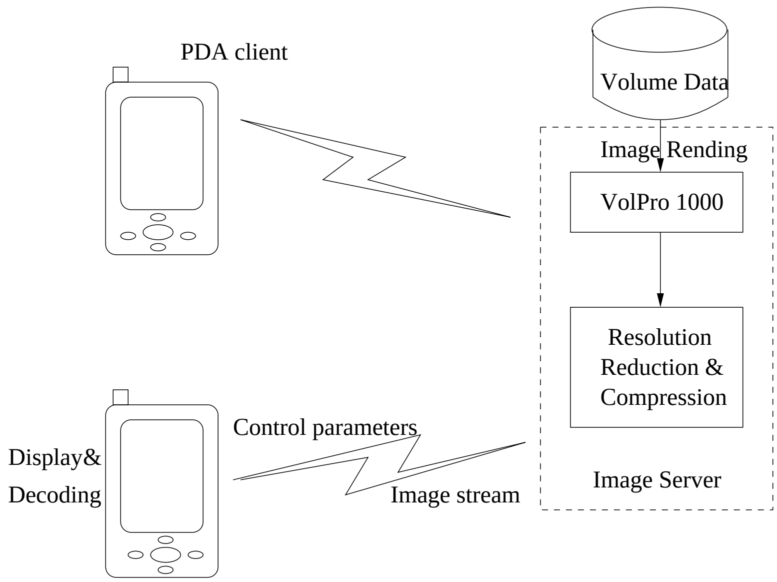

Figure 1. System Architecture

subsampling is more convenient to generate different versions of the same content to fit for different requirements and constraints. This approach can meet a wide range of varying needs dynamically. In the project, the server subsamples 512×512 RGBA image to client's screen sized RGB images omitting alpha channel that defines the transparency of the pixel, as the 3D volume projection is performed on server. Figure 1 shows the architecture of the system.

The overall process of easy-to-use medical visualization on Pocket PC is:

- Operations on Pocket PC:
  - The Pocket PC user creates a mobile connection and starts sending rendering/viewing parameters.
  - The Pocket PC decodes the received image data, and display the image on the screen.
  - The Pocket PC user may change visualization parameters and send them to image server.
- Operations on Image Server:
  - The Server generates volume rendered images and content adaptation to meet the resource constraints of Pocket PC.
  - The Server compresses, encodes images, and sends to Pocket PC.
  - The Server continuously grabs visualization parameters from the Pocket PC, and updates the rendered images to be sent to the Pocket PC.

The rendering task is distributed to the powerful server. The server generates volume rendered images according to the client's rendering/viewing parameters, then compress them and sends to Pocket

PC. The users feel the rendering is performing on the client. Since server can handle multiple users' request, multiple users at different locations can join the visualization session. Due to fact that the patient's medical records are confidential, the access to the server is restricted to the authorized users and the data to be transmitted are encrypted with 128-bit Wired Equivalent Privacy (WEP) for security purpose.

2.2. Image Compression

When client user manipulates visualization system on Pocket PC, the image server continuse grabs visualization parameter from Pocket PC, generates, transmits, and displays image sequence on Pocket PC. Since the image sequence has vast amount of data and the wireless bandwidth is low, the images are need to be highly compressed at server side to minimize transfer time. We do not adopt video coding algorithm to exploit temporary redundancy, because the temporary redundancy is low in most volume pictures. Each picture should be compressed independently. Since the processing power of mobile handheld device is low, the compression algorithm has to be computational inexpensive to avoid long decoding time. Hence, there exists trade-off between compression efficiency and computational complexity. The image compression algorithm is desired to be simple in computation and efficient in compression.

We focus on optimizing overall visualization performance when compressed images are transmitted to low processing power Pocket PC over bandwidth-limited wireless network. Since image-based diagnosis requires high resolution images, we need lossless image compression to keep all detail information. However, when images are not for diagnosis, e.g. when displaying a moving object, we may not need high-resolution image. Fast progressive display can be used in such situations where timely partial figures are desirable. Fast progressive display is motivated for real time application. When the object keeps still for diagnosis, we then need high-resolution picture. Hence we set a switch for lossy image display and lossless image display in the system. For example, when client user zooms and rotates image, the server uses lossy image compression, when user stop to diagnose with image, the server switches to lossless image compression.

Among, transform-based image compression, wavelet-based image compression techniques, such as SPIHT, JPEG2000, are widely used because of their high compression efficiency.[9] However, The decoding for SPIHT and JPEG2000 is slow for real time visualization on Pocket PC. Using IPAC 5500, the last step of SPIHT decoding of a 256×256 8 bits gray image, the inverse wavelet transform to generate image pixel value takes about 0.8 second. For color images, the decoding is much slower than gray image. Hence, wavelet-based image compression schemes are computational expensive for real time visualization on current mobile Pocket PC client. DCT based image compression is faster than Wavelet-based compression. However, they are still not the optimal choice for the trade-off compuational complexity and compression efficiency in real time application.

We adopt a fast lossless image compression.[7] Unlike transform-based compression techniques, this approach uses predictor in the preprocessor and Golomb-Rice code in entropy coding. The predictor uses two neighboring pixels as reference. We use L to represent smaller neighboring value, and H to represent larger one. We use Δ to represent the difference H - L, and treat Δ as the prediction context of P. Figure 2 shows the distribution of the intensity of the new pixel for a given context Δ. P lies in the range [L, H] about half time, requiring one bit to encode, and when P is out of range, another bit is used to indicate above or below the range. The probability of out-of-range falls sharply. Golomb and Rice codes are used to encode how far the value from the range. The codes are parameterized by a positive integer parameter m. The n-bits symbol is splitted into two parts: The most significant n-k

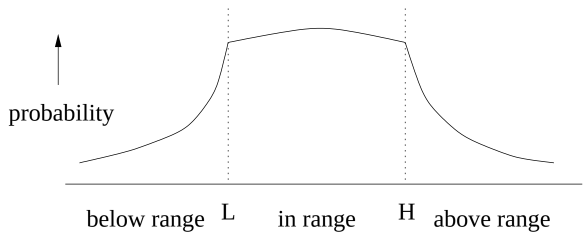

Figure 2. The distribution of the intensity of new pixel

bits and the least significant k bits. The least significant bits are coded by adjusted binary code. The most significant bits are coded in unary. A parameter estimation technique is described in[7] to select parameter k. It cumulatively counts codeword length for all possible parameter values, and selects the best value. In our project, to further speed the compression, we build a parametric lookup table off line, and use this lookup table to select appropriate parameter k at run-time. The parametric lookup table is built by performing parameter estimation off-line on many typical images to find most optimized parameters. Using lookup table does not hurt compression much since in practice the parameter estimation converges quickly to the best value.

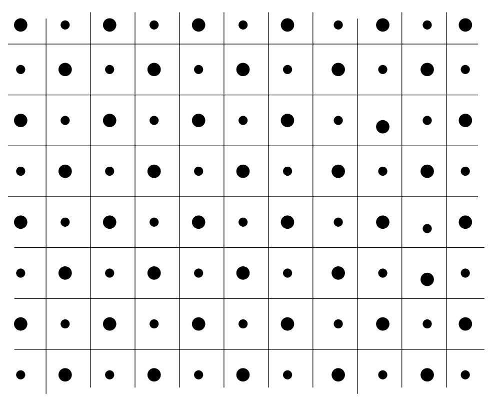

Figure 3. Two level progressive image compression

When client displays moving targets, progressive displaying improves frame rate and the smoothness of scene transition. Progressive image compression is implemented by multiple level progressive compression. Figure 3 shows a two-level progressive compression. At the beginning the first level, the pixels (big dots) form grid and are coded by the above descripted compression method. At the client side, after decoding, the midpoints (small dots) are predicted in this level. In the next level, the small points are coded in the same way. At the client side, the midpoints are decoded to update the predicted values.

2.3. Image transmission

The built-in network modules support both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) in transport layer. The TCP use automatic retransmission (ARQ) to combat channel error. When client receives packets, and then sends acknowledgement to server. When packet loss occurs, the server has not received acknowledgment from client, it will retransmit the packet. Hence the transmission is reliable. Retransmission will decrease the actual transmission rate. Intuitively, one would expect that as the packet loss probability goes up because of increasing bit error rate. While the UDP transmission is unreliable. When client receives packets, it does not send acknowledgement to server. To combat channel error, we could employ forward error coding (FEC) to the data. The basic concept of FEC is to add redundant information to the data. The errors in the transmission could be corrected by using the redundant information. Adding redundant information will also decrease the actual transmission rate.

Whether TCP or UDP with FEC is more efficient is a function of the quality of the service, packet size and channel characteristics. We use Reed Solomon (255, 223) code in UDP transmission. The RS (255, 223) code adds about 14% redundant bits and can correct up to 16 symbol errors in one 255 symbols block. For ARQ in TCP, suppose P_{eb} is the BER of a binary symmetrical channel, and L is the length of a packet. The packet error probability is:

$$P_{ep} = 1 - (1 - P_{eb})^L, \tag{1}$$

We use the correctly received packet ratio at the receiver P_{cp} as a measure of the quality of the service. To maintain a given P_{cp}, the following condition should be satisfied:

$$(1 - P_{ep})(1 + P_{ep} + P_{ep}^2 + ... + P_{ep}^T) \geq P_{cp}. \tag{2}$$

That is, the parameter T should be such that the above inequality (2) holds. Under this condition, the mean retransmission ratio can be computed as:

$$R = P_{ep}(1 - {P_{ep}}^T)/(1 - P_{ep}) = P_{ep}P_{cp}/(1 - P_{ep}) \tag{3}$$

Suppose in BSC channel, the packet length is 1024 bits, the correctly received packet ratio is 1. The mean transmission ratio is shown in Figure 4. The RS (255, 223) code has 14% redundant bits and can correct 6.2% symbol errors. If we use one byte to represent one symbol, the corresponding BER in BSC channel is 0.008. Hence, when channel BER is less than 10^{-5}, the ARQ is more efficient. When channel BER is higher than 10^{-5} and less than 0.008, the FEC is more efficient. High channel BER is one of the features of wireless communication. Hence, UDP with FEC is more efficient in wireless communication. There are two other reasons for using UDP over TCP in real time wireless transmission application. The UDP header is shorter than the TCP header, which further reduces the amount of bandwidth the data will be consuming. Second, in wired network, the packet loss is primarily due to network congestion as routers discard packets. On detecting packet loss, TCP's transport receiver responds by invoking congestion control and avoidance algorithms to slow the transport sender and thereby reduce the network load. However in wireless communication, bit errors are not caused by network congestion. The better way is not to slow down transmission rate.

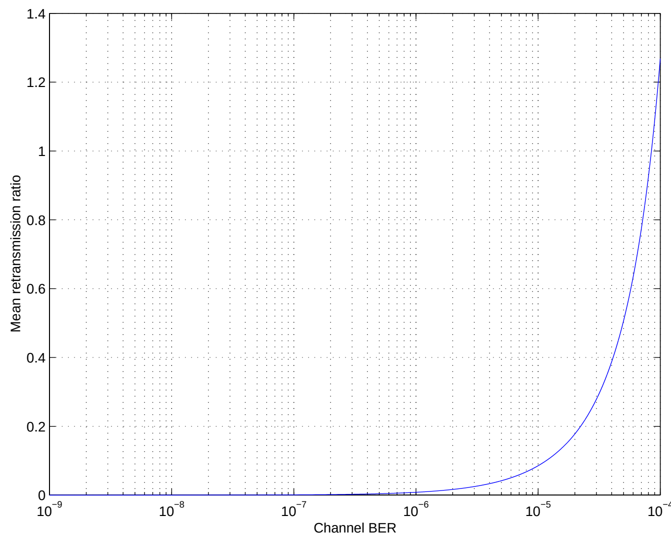

Figure 4. Mean retransmission ratio vs. channel BER

3. EXPERIMENTAL RESULTS

Hardware for the easy-to-use visualization system includes wireless access point, volume image server, and Pocket PC client. On the server side, we use Dell dual 2.6 GHz Xeon CPUs Server with VolPro-1000 card to rendering volume data. The VolPro 1000 provides high quality real time volume rendering. On the client side, we use Compaq iPAC 5500 mobile Pocket PC with 400 MHz Intel processor, 128M memory, and 64K color 16-bit 320×240 LCD display. iPAC 5500 integrates 802.11b wireless card, and reduces bit-depth for 24 bits color image display. We use embedded Visual C++ 4.0 as development toolkit.

We adopt the fast and simple lossless image compression to achieve best trade-off between compression efficiency and computational complexity. The decoding time for a 256×256 8 bits gray image is 0.125s. The decoding is fast at the trade off of the compression efficiency lower than wavelet-based compression techniques. The lossless compression ratio is from 1.6 to 2.4 for the test images. RS(255,223) FEC coding scheme on the UDP socket transport is employed to combat packet loss in wireless transmission. To evaluate the overall performance of the system, we test the lossless transmission of 256×256 24 bits color image sequence. The frame rate could reach to 5 frame/second. With lossly compression and progressive display, the frame rate could further increase, and the frame rate is dependent on the Quality of Service. Figure 5 shows an example of tomographic image visualization on iPAC 5500. Experimental results show that this system is practical for clinic diagnosis.

4. SUMMARY AND DISCUSSION

In this work, we have implemented an easy-to-use medical visualization system on mobile handheld device through WLAN. The system provides physicians a very convenient way to interactively access image data using their Pocket PC without the restriction of staying in the fixed location. Because of the huge gap between image server and Pocket PC client on processing power, the Pocket PC client used only for display image and interaction editor to change visualization parameters. Most render tasks are

Figure 5. Example of tomographic image visualization on Pocket PC

moved to the server. Since the wireless bandwidth is limited, we adopted a simple image compression scheme to achieve best trade-off between computational complexity and compression efficiency. A RS (255, 223) code is employed for forward error coding on UDP socket connection. Experimental results the system is practical for clinic application. We believe the system will provide advance service for the doctors in their diagnosis.

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