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TELEMEDICINE FOR DISASTER RELIEF: A NOVEL ARCHITECTURE

S. OLARIU, K. MALY, E. C. FOUDRIAT, C. M. OVERSTREET, S. YAMANI
Old Dominion University, Norfolk, VA, USA
{olariu,maly,foudr_e,cmo,yamany}@cs.odu.edu

T. LUCKENBACH
Fraunhofer FOKUS, Berlin, Germany
luckenbach@fokus.fraunhofer.de

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Disaster response and recovery require timely interaction and coordination of public emergency services in order to save lives and property. An important role in this effort must be played by wireless telemedicine whose mandate is to bring to the scene of the disaster the experience and expertise of medical personnel that can direct and supervise paramedics in providing necessary life-support services. The main contribution of this work is to propose Wireless Interactive Remote Medicine – a wireless system architecture support for telemedicine that incorporates leading-edge image compression technology, a robust interactive visualization tool, and a high-performance wireless multimedia network.

Key words: telemedicine, disaster management, dependable systems, wireless networks, image compression, surface reconstruction.
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1 Introduction

Natural and man-made disasters, including hurricanes, earthquakes, tornados, tidal waves, forest fires, chemical leakages and contamination and water pollution, pose a serious threat to society by taking a heavy toll in human lives, destroying industrial infrastructure and production capacity, interrupting supply lines and hampering economic activity [10,26].

There is an imperious need to bring medical expertise to the scene of the disaster in order to provide professional-quality, on-the-spot assistance to the victims. Telemedicine has emerged as one of the most important paradigm shifts that hold the promise of revolutionizing health care delivery by offering world-class healthcare to geographic locations where it is either impossible or impractical to deploy expensive medical infrastructure or highly qualified personnel. The American Telemedicine Association (ATA) is the leading resource and advocate promoting access to medical care for consumers and health professionals via telecommunications technology. ATA seeks to bring together diverse groups from traditional medicine, academic medical centers, technology and telecommunications companies, e-health, medical societies, government and others to overcome barriers to the advancement of telemedicine through the professional, ethical and equitable improvement in health care delivery [3].

Telemedicine is predicated on the availability of high-speed, high-bandwidth wired networks. As a rule, however, in areas afflicted by disasters and other emergency situations the existing networking infrastructure is no longer operational, hampering the use of telemedicine where its services are desperately needed. A new kind of telemedicine is needed – one that relies on low-bandwidth, rapidly deployable mobile systems that are self-organizing, heterogeneous, and that do not rely on pre-existing infrastructure. It is painfully clear that robust wireless communication systems and avant-garde medical imaging are the key enabling technologies that can bring to the scene of the disaster the experience and expertise of medical personnel that can direct and supervise paramedics in providing necessary life-support services.

The main contribution of this paper is to propose a wireless system architecture for telemedicine, that we call *Wireless Interactive Remote Medicine* (WIRM), which relies on leading-edge image compression technology, a robust interactive visualization tool, and a high-performance wireless multimedia network.

The remainder of this paper is organized as follows: Section 2 discusses the state of the art in telemedicine and its applications. Section 3 discusses the main components of WIRM and the main challenges associated with the project. Section 4 delves into the details of a novel 3D compression technique developed by one of the authors. Section 5 discusses the second major component of WIRM, an interactive remote visualization tool (IRI) developed at Old Dominion University. Section 6 presents the details of H3M and eH3M, the wireless architecture that supports WIRM. Finally, Section 7 offers concluding remarks and maps out directions for future work

2 Telemedicine – State-of-the-art

In the past few years we have witnessed an increased role of computers in various medical applications [3,6,9,10,38,39]. This has resulted in an increased acceptance by the health care industry of the need to integrate computer technologies in the delivery and management of health care. Indeed, it is encouraging to see that due to advances in techniques such as computer aided surgery, virtual surgical planning, and real-time navigation systems, medical procedures that were deemed impossible or very dangerous a few years ago are becoming more feasible and enjoy a higher success rate. However, the use of such technologies in interactive telemedicine applications and in medical training is still in its infancy. The main reasons for this situation are the technical challenges involved in sharing high-fidelity visualization, real-time 3D modelling and manipulation, and real-time biological simulation modules over the nodes of the telemedicine and remote medical training network, especially if the mode of communication is wireless.

The primary goal of any remote medicine application, either in training or in telemedicine, is to help health care providers do their work more efficiently and effectively, and to improve the competitive position of integrated health care delivery networks. By achieving such a goal, they help overcome imbalances in access to medical expertise, integrate geographically dispersed services, improve the quality of health care in under-served and remote areas, and maximize the impact of existing technical resources. This goal becomes more tangible in cases where patient access to specialized medical expertise is either non-existent or very difficult, as is the case in disaster areas. Such is the case, for example, when securing victims of natural disasters, terrorist attacks, providing first-aid to landmine victims, to fire-fighters and other support personnel.

Integrating wireless communications for different telemedicine is an emerging application area. The concept covers a much broader range than just supplying a person with a mobile phone, since it equally involves the use of swiftly moving vehicles that are equipped with high quality wireless systems, to assist patients in under-served regions or in disaster areas. Most current telemedicine systems only provide the user with the ability to transfer files (images, video or audio clips, medical records, etc.) from one location to another [7,10,11,16,41,45]. Only a few systems provide more interaction with the remote location through live audio and/or video capabilities [39,42,43]. Indeed, the wireless telemedicine systems currently available use a limited bandwidth of 5 Kbps per phone line, which in turn limits the typical aggregate transmission rate to about 20 Kbps. The video images are captured at 30 fps, but because the wireless bandwidth is limited to about 20 Kbps, the images are transmitted in *slow scan* fashion at about one image every 2.5 seconds at FCIF resolution (320-bits X 240-lines X 24-bit depth). Some systems allow on-the-fly tradeoffs between motion handling and resolution, and the emergency personnel can capture specific images or video clips at 5 fps, which can be sent in a store-and-forward fashion [3].

While there is no doubt that current medical training and telemedicine applications have great impact in enhancing patient care by streamlining administrative processes, by giving clinicians new tools to increase their efficiency and by providing quality medical services to remote sites, we consider these systems as static in the sense that no digital tools are available to manipulate, analyze and interact with the medical data being transferred. Even though audio/video capabilities exist, there must be other communications tools to enable users to interact with each other and with the data at the same time. These tools may include, for example, medical image analysis tools, 3D medical visualization and manipulation, and audio/video signal analysis tools. Also innovative compression and remote visualizations techniques are needed in order for the faithful and real-time wireless transmission of video/audio signals and 3D data for interactive visualization and consultation [2,7,47].

To illustrate the difference, consider first the example of an emergency personnel communicating with a remote expert for consultation on a landmine victim case. Current ISDN telemedicine capabilities enable the transfer and visualization of a video signal showing the patient's situation, record and related medical images. These can be done on store-and-forward protocol. The expert can download the data, study them, recommend an action plan and communicate back using audio/visual facilities.

In our view, a true dynamic solution would enable the real-time transmission of video/audio signals, 3D representation of the victim situation and scene, medical images and available records. The expert can highlight, in real-time, regions of interest in the images, obtain a 3D reconstruction of the structure of interest, manipulate the resulting 3D, perform measurements and analysis, discuss the situation using editing tools, and sketch an action plan online. Moreover, all this is done while the other users or practitioner are actively involved in the session, sharing tools and steering the session at certain instances of time. In fact, the whole session could be stored for further consultation or to assist the practitioner to perform the specific tasks discussed during the session.

3 The WIRM system architecture

The proposed WIRM system architecture for telemedicine in support of disaster relief applications consists of several modules. The first module is the data acquisition module. One key component of this module consists of a sensor corresponding to a specific application (e.g. endoscope, telescope, intra-oral camera). The sensor will be responsible for acquiring visual data that is transmitted as a video stream to the computer vision modules at the examiner unit. One of these modules is responsible for the 3D reconstruction of a surface model representing the visualized structures. Another module is responsible for detecting and tracking the position of the sensor relative to a common coordinate system. The other component of the data acquisition module consists of additional patient medical data that was either acquired off-line (e.g. CT, MRI, X-Rays, etc.) or that is being acquired on-line (e.g. Ultrasound, EEG, ECG, etc.). In our WIRM implementation, we will concentrate on CT and/or MRI medical volumes that were acquired off-line since they are currently considered as routine diagnostic procedures. These volumes are transmitted to the medical image analysis modules that consist of a segmentation module and a multi-modal fusion module [45]. For each medical volume, the segmentation module is responsible for automatic detection, separation and 3D reconstruction of the anatomical structures of interest to the specific application at hand. The multi-modal fusion module is used to integrate the structures obtained from the two modalities (e.g. bone from CT and soft tissues from MRI) into one 3D model.

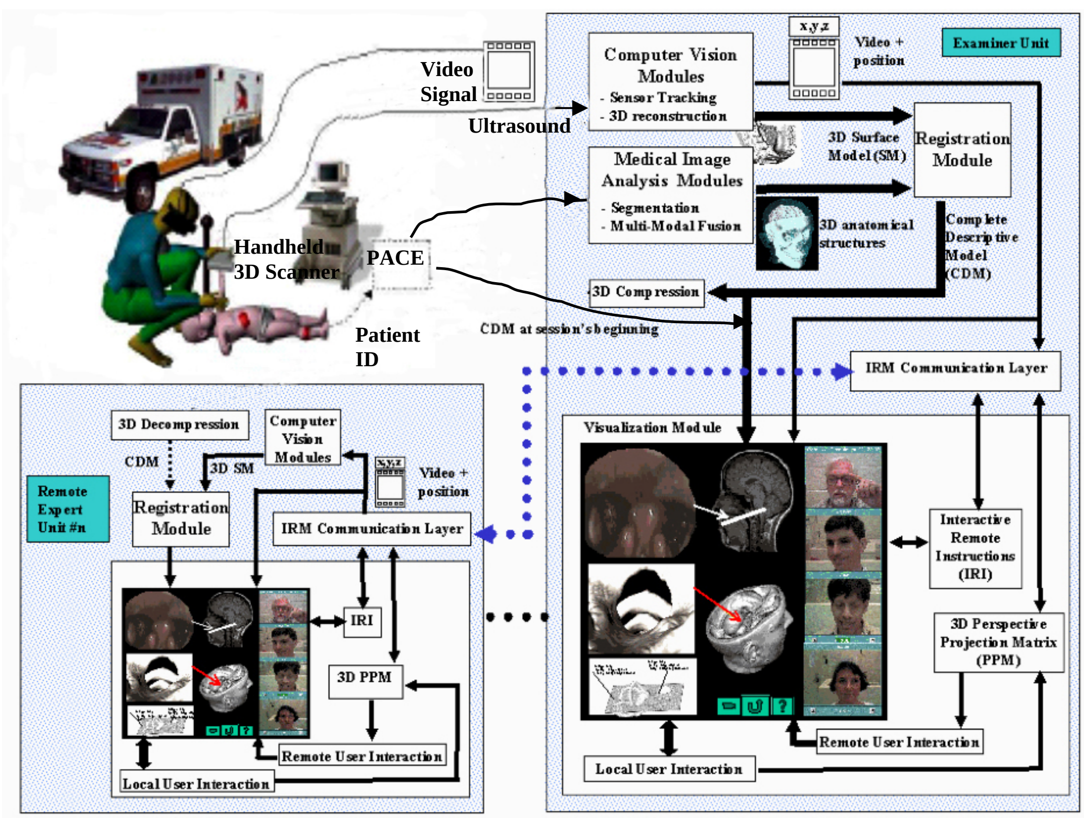


Figure 1: *WIRM system architecture for disaster management applications. The system has several modules. The first is the data acquisition module which consists of video capturing, 3D scanner and 3D/traditional ultrasound system. The data acquisition module may have a connection to a PACS system if available. The acquired data is fed into the corresponding processing modules. Registering the output of these modules results in the Complete Descriptive Model (CDM) of the anatomy of the visualized organs and their underlying structures. An interactive visualization module provides a real-time, dynamic interface between the examiner at the patient site and experts at remote sites. The connections between sites are based on a wireless network architecture.*

Figure 1 illustrates the proposed WIRM system architecture specialized to the case providing emergency care to a landmine victim. The system includes the following major components:

- A novel 3D compression paradigm that will make it possible to transfer of 3D data over the bandwidth-constrained links, making telemedicine support for the victims of disasters and emergency situations over wireless networks technologically feasible and economically viable
- An Interactive Remote Visualization tool (IRI) developed and tested at Old Dominion University
- A robust broadband wireless architecture -- the Hierarchical Heterogeneous Highly Mobile Network (H3M, for short), that will provide a flexible and cost-effective platform for rapid deployment in support of disaster relief, search-and-rescue and similar emergency situations-related applications.

An important aspect of disaster management is *training* of response personnel, in such a way as to guarantee operational readiness in the case of an emergency [4,9,13,15,19]. One of the major goals of the WIRM architecture (reflected in the versatility of its components) is to provide an obvious and intuitive training tool. This is in sharp contrast with current applications that only provide static information in form of stored text, images and videos that can be triggered by the student response to some predefined situations. In our view, the next generation of emergency medical training applications will be able to offer an environment where the students and their mentors at distant locations can download information about new patients, perform analyses, examine the 3D representation of the actual biological structure under study using high-fidelity visualization tools that enables real-time navigation in an accurate metric space, perform virtual dissection using virtual instruments and with real biological tissue simulation. As before, all this while their mentors or experts interacting with them in real-time and guiding them to the correct procedure, pointing to weaknesses in their operations and highlighting common mistakes. Each student will be able to store the whole session for future reference and for assessing the progress each has made. Of course, such systems will not completely replace the need for real-life training; its main objective is to expose students to more cases and situations, some of which may be rarely encountered in their real-life training, and also to provide them with extended practice time that does not require the specialized medical setup and resources needed for the real-life training.

3.1 WIRM challenges

For the proposed WIRM system architecture to be of practical value for medical training applications, many technical challenges need to be addressed and resolved. These challenges include the following.

3.1.1 Dealing with a dynamic environment

As discussed before, the main difference between the proposed WIRM system and current telemedicine and medical training systems lies in the dynamic interaction between local and remote units. Although it is widely advertised that the technology for implementing interactive digital TV and other promising applications of the National Information Infrastructure (NII) is currently available, in fact it is not. Based on our experience in working with the State of Virginia on the TELETECHNET project, we have realized that several technical difficulties are still hindering the progress towards a scalable, affordable, manageable, developer-friendly, and user-friendly NII. Current NII systems enable and manage, in a limited way, groups to have multimedia communication and collaboration. However, the feasibility of scaling these groups to hundreds of participants is still questionable. This is because it will necessitate management tools for handling the various, highly dynamic, multimedia streams and allocating bandwidth to them; it will further require new protocols for controlling these streams, new protocols for student-teacher interactions. Perhaps even more importantly, we need to improve the performance of existing collaboration and conferencing tools by an order of magnitude by such techniques as reliable multicasting for data traffic and efficient utilization of the underlying network. Once one has a system such as the proposed WIRM system, one naturally would want to extend it to the home and office user. One clear candidate for this potential is to use the existing TV cable infrastructure as the network. Now a whole new set of unresolved issues arise such as the lack of interoperability standards for digital multimedia communication protocols. Most crucial to an application such as WIRM is user acceptance. We need to measure reactions by physicians, teachers and students to the user interface, develop a new paradigm of consulting, teaching and learning, which truly takes advantage of the technology but is still acceptable and accessible to the average, non-computer science physicians, medical students and disaster response experts.

3.1.2 Biological tissue simulation

The proposed WIRM system architecture needs high-caliber simulation tools, especially for the purpose of training response personnel. These simulation tools must be sufficiently realistic to help the student acquire the correct knowledge and skills. Such a requirement can only be achieved by designing and implementing a realistic deformable biological tissue model to be used in virtual reality surgery training simulators. These tissue models must be efficient and realistic in estimating tissue behaviour. They must also be realistic in modelling interaction forces. The most accurate way to model tissue behaviour is to use finite element models. However these models are too slow because of their computational complexity. The other choice is to use simple, so-called *physics-based* models, which are computationally fast, but have limited physical basis.

Visual realism and real-time interactions are essential in surgery simulation. Real-time interaction requires that any action from the operator generate an instantaneous response from the stimulated organ, whatever the complexity of its geometry. Moreover, since all the organs in the human body are not rigid, their shape may change during an operation. Consequently, the realism of the deformations is another key point in surgery simulation. This realism can be enhanced by the introduction of force feedback devices, which allow for a better immersion in the virtual world. When coupled with precise computations of the forces, it may be possible for the surgeon to feel haptic sensations close to reality.

It has been shown that the physical models have numerous advantages over kinematic models for computer animation. Among these physical models, elastic models have been extensively described in the literature. The particular shape of an elastic body is a function of both the internal stress and strain within the object and the external forces applied to it. Generally, some modifications or simplifications are made to elasticity theory in order to give a particular behaviour to the deformable body.

For the WIRM system to achieve virtual-realism and also real-time response, we need to integrate all the requirements for a realistic simulation (i.e. real-time modelling of elastic tissue, real-time visual and haptic feedback). Real-time interaction can be possible by the pre-processing of elementary deformations coupled with speed up algorithms. Also using linear elastic deformations enhanced by taking into account biomechanical results on soft tissues will enable WIRM to give a more realistic behaviour.

3.1.3 Computer Vision and Medical Image Analysis Modules

These modules are essential parts of the WIRM system. The computer vision module has to perform two tasks, namely, 3D surface reconstruction from video images and sensor tracking. 3D reconstruction from video images has attracted the attention of researchers for many years [8]. One of the authors has been involved in this area of research for many years and has proposed a new technique using fusion of a modified *shape-from-shading* technique and range data in the reconstruction of the human jaw from a stream of intra-oral images.

4 A novel 3D data compression technique

The main bottleneck hampering the performance of wireless telemedicine and medical training applications lies in transferring 2D/3D data over limited bandwidth networks. For example, a typical brain surface extracted from a high resolution MRI or CT volumes can range from 20 to 30MB. Even using the best currently available compression techniques, the compressed surface will be around 2MB. A fundamental part of WIRM is a novel 3D data compression scheme that is being implemented and tested. The idea is based on the Surface Point Signature (SPS) representation scheme introduced lately by Yamany and Farag [48-50]. The SPS scheme captures the surface curvature information, seen from certain points and produces images, called surface signatures, at these points. The SPS representation was successfully used in near real-time registration [48], to match objects in 3D scenes in the presence of clutter and occlusion [49], and recently in the coding of 3D objects [48]. We propose to extend the definition and application of the SPS representation to enable compression and decompression of 3D objects. WIRM uses a small number of SPS images to represent the 3D surface. These images are compressed and sent to remote sites where they are decompressed and the object is re-synthesized. Depending on desired resolution, the compression ratio can be high and we can also achieve progressive enhancement in the re-synthesized object by streaming more SPS images.

4.1. SPS image generation

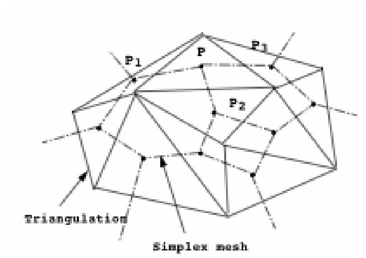
Rather than depending on the 3D coordinates of the point on a free-form surface, the SPS framework obtains a signature image at each surface point. The signature, computed at each important point, encodes the surface curvature seen from this point.

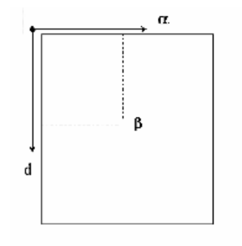
In its general form, a free-form surface is composed of unstructured triangular patches. There exists a dual form consisting of unstructured simplex mesh [50] as shown in Fig. 2(a). A topological transformation is used to associate a k-simplex mesh to a k-triangulation or k-manifold. This transformation works differently for vertices and edges located at the boundary of the triangulation from those located inside. The outcome of this transformation is a (k-p)-cell associated with a p-face of a k-triangulation. In this work, a 2-simplex mesh form is considered in the curvature calculation. Let P be a vertex of a 2-simplex mesh having three neighbors P_1, P_2 and P_3. Assuming that these points are linearly independent, they define a unique plane π with normal $\vec{U}_P$ and a circle of (finite) radius r in π. The four points $P, P_1, P_2,$ and P_3 are circumscribed by a sphere with center O and radius R as shown in Figure 2(b). The simplex angle θ shown in Fig 2(b) is defined as

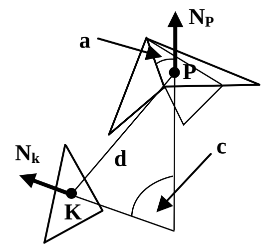
$$\sin\theta = \frac{r}{R}\, sign(\vec{PP_1}\cdot\vec{U}_P).$$

Note that this definition assumes that the three neighbors are linearly independent, thus $r \neq 0$. The simplex angle θ is calculated as shown in Figure 2(b). Clearly, θ is related to the mean curvature *H* of the surface at the point *P*.

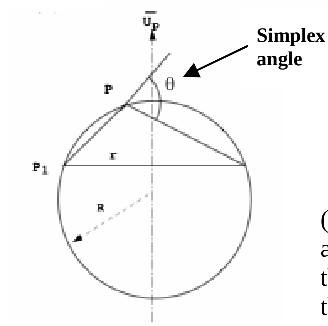
Our idea is to use this curvature measure to obtain a reduced representation of the surface at certain suitably chosen points. This reduced representation encodes the curvature values at all other points and creates an image. This image is called a *signature image* for this point because the change in curvature values with the distribution of all points forming the surface relative to the point in study is unique. The signature image is generated as shown in Fig. 2(c). More details can be found in [47].







(a) Duality between Triangulation and Simplex mesh



(b) Simplex angle calculation

$\cos \alpha = (k - p) \bullet N_p$

$d = | k - p |$

$\cos c = N_k \bullet N_p$

(c) SPS generation: Any two points P and K on the surface are related by the distance "d" between them and the angle "a" as shown above. Mapping d & a as the two image axes, and doing the angle c as gray value, we can generate an SPS at P.

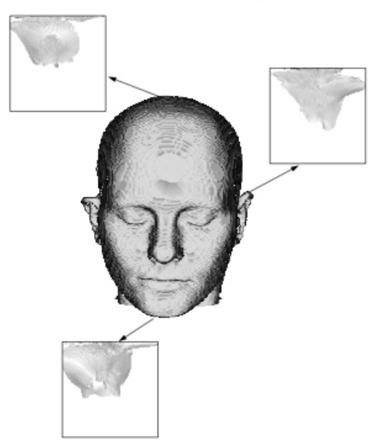


Figure 2: *An illustration of the details of SPS generation*

The same not true, however, for surfaces of revolution (SOR). We do not generate these images at all surface points; instead we ignore the points with low curvature value. These points are redundant and do not serve as landmarks for the object. The simplex angle is used as a criterion to reduce the surface points and use only a subset $A \subset S$ in the compression process, where *S* is the set of the simplex mesh points. The subset *A* is defined with respect to a threshold λ such that *A* contains the landmark regions of the surface. More specifically,

$$A = \{P_i \in S \mid and \mid \sin\theta_i \mid \geq \lambda, \lambda \geq 0\}. \quad (1)$$

The signature image is generated as follows: for each point *P*, defined by its 3-D coordinates and the normal $\vec{U}_P$, each other point P_i on the surface can be related to *P* by two parameters:

- the distance $d_i = \| P - P_i \|$ and
- the angle $\alpha_i = \cos^{-1}\left(\frac{\vec{U}_P \cdot (P - P_i)}{\| P - P_i \|}\right)$.

At each location in the image we encode the angle $\beta_i = \cos^{-1}\left(\vec{U}_P \cdot \vec{U}_{P_i}\right)$. Clearly, this represents the change in the normal at the surface point P_i relative to the normal at *P*. Due to the fact that we are ignoring the cylindrical angular degree, the same pixel in the SPS image can represent more than one 3-D point on the surface. We solve this problem by taking the average of their angles β_I and encode it in the SPS corresponding pixel location.

Consequently, one can view the SPS framework as a transformation mapping a 3-D domain to a 2-D domain. This transformation can be represented by the integral

$$SPS_P(d, a) = \oint_{P_n} Curv(P_n)$$

where *Curv(P)* is the curvature at *P*. Quite surprisingly, although it may look as though by applying the transform we are loosing information, in reality we can re-synthesize the original object accurately from the SPS images

As an illustration, consider a sphere: all the points on the sphere have the same curvature and normal directions relative to each other. Thus, all SPS images will be the same. Taking only one SPS image at one point location, we can re-synthesize the sphere by sampling back the 3-D circle formed by each point on the SPS image, thus the inverse SPS (iSPS) transform. The re-synthesized sphere will be identical to the original. This is also true for a cylinder if the point used is on the cylinder axis. Using the formula

$$S_{original} = \bigcap_{n=1}^{\infty} iSPS_{P_n}(d, a)$$

for non-regular surfaces or objects, the original object can be re-synthesized accurately by intersecting the iSPS volumes obtained from an infinitely large number of SPS images. In other words, each iSPS produces a harmonic object (sphere, cone, cylinder, etc.) and every object can be synthesized from the intersection of these harmonic objects.

In fact, it can be shown that the original object can be re-synthesized with acceptable accuracy using only a *limited* number of SPS images as illustrated in Figure 3. Using this technique, a 20MB high resolution MRI brain surface can be compressed into 20, 1KB compressed SPS images.

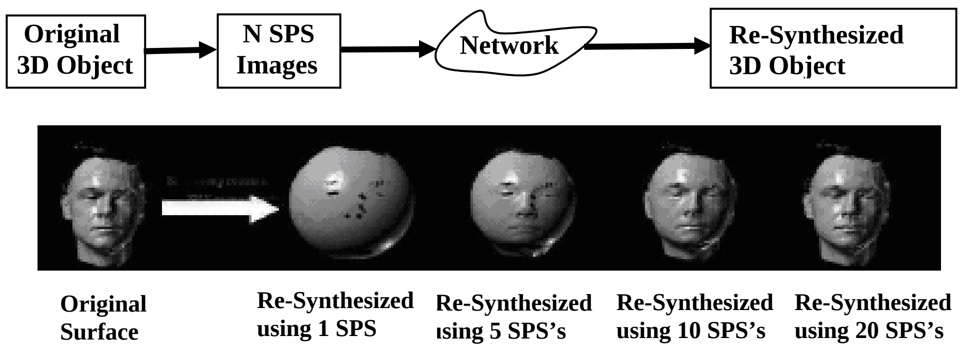


Figure 3: *Illustration of 3D compression using SPS*

5 Interactive remote visualization

For more than ten years our work at Old Dominion University in the area of Multimedia Collaborative Computing encompasses both synchronous (real-time) and asynchronous forms of collaboration [28,29]. For synchronous collaborations, we have demonstrated remote shared visual workspaces that support selective multi-way audio and video, document sharing with editing and slide presentations. We have developed shared workspace tools for several forms of collaboration involving professionals who may be geographically dispersed. These tools can be used for treatment decisions by an oncologist or surgeon looking at the same picture as a radiologist. Each can manipulate and annotate the image for other participants.

Shared visual workspaces are abstractions that denote a collection of objects (e.g. documents, images, programs) and the tools used to view and change them. Each participant in the collaboration can have the same visual representation of the workspace(s) and the same facilities for viewing or modifying the objects with all other participants observing the interactions.

5.1 Interactive Remote Visualization architecture

Experience shows that in disaster recovery, effective, efficient and reliable communication among care providers is crucial. The software architecture of IRI is designed to support sharing of images and other software tools among many participants along with prudent management of limited and varying communication bandwidth. Figure 4 presents the software architecture of IRI that is constructed to allow users with different bandwidth capabilities to participant in sessions. The main components are:

- A Session Manager (SM) that registers the presence of valid participants as they join or leave sessions. This information is used to distribute data to all participants and to allow everyone to see a list of current participants,
- A set of Token Managers that are used to synchronize updates of shared documents and images. While any participant and manipulate shared documents (with updates visible to

all others), in fact synchronization requires modifications be done by only one person at a time,

- A Log Server that records significant session events for later examination by technical support personnel if desired,
- Observers that receive all communications as if they were also participants but provide services such as recording sessions for archiving and later playback. Issues and an implementation for recording and replay in the IRI environment are discussed in [12],
- A Group Communications server that provides the necessary communication services (for example, reliable or unreliable, encrypted or clear-text) needed by other software components, and
- A Gateway capable of handling multicast disabled participant machines and machines connected with reduced bandwidth. This allows individuals with restricted network capabilities to still participate in sessions. They can still provide data but without impeding, for example, sharing of high resolution images among other participants. For more information on the Gateway design see [20].

The flexibility, security, and reliability provided in the IRI architecture are necessary in telemedicine communication systems supporting disaster recovery.

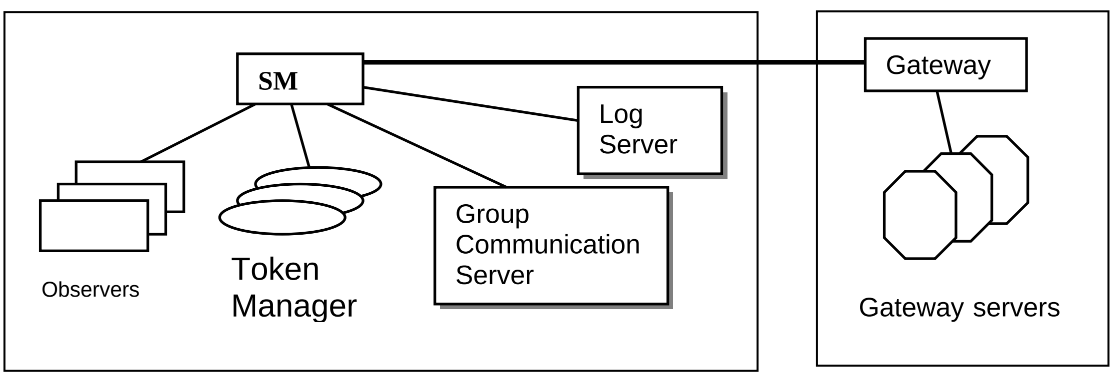


Figure 4: *Software architecture of Interactive Remote Visualization*

5.2 Interactive remote visualization interface issues

The main decision is how closely the collaboration environment will be integrated with an existing computer environment. We agree with the prevailing view that great advantage is gained from making familiar programs readily available to participants. In most cases these tools have been written for a single user -- they assume a single input source and present a single view. Since it would be impractical to modify even the most-used tools, it is necessary to provide adapters that allow any single-user tool to be used unchanged in multi-user environments. Such adaptation can be accomplished by interposing, between the tool and its users, agent processes that present a single input stream to the tool and replicate its output to multiple viewers. Next we choose between a single activation of the workspace and multiple replicas [1]. While the single-workspace model is simpler and synchronization of user views much easier to accomplish, it may result in poor interactive performance. Processing times in the agent, network latencies and bandwidth limitations are likely issues. The replicated-workspace alternative may improve performance but at a cost of complexity in protocols for reliably delivering duplicate input to all copies. If some input is not duplicated at all copies, it may be difficult to resynchronize the states of the replicated tool instances (and data objects). An equally serious problem is duplicating the total execution environment for tools at all sites, particularly when extensive customization is common. In our work we have used both approaches (sever shared tools or replicated tools) based on the communication and computational aspects of different tools. Most of our most recent work has been based on the single-workspace model.

We must also consider whether each user should see exactly the same view of the tool output (the "what you see is what I see" -- WYSIWIS -- model). Although exactly duplicated views are difficult to achieve on heterogeneous displays, we believe this is the best strategy for adapting existing tools. Additional design decisions that are reflected in IRI include

- provision for dynamic addition or removal of users participating in a shared visual workspace,
- the ability of users to participate in multiple shared workspaces concurrently, and
- shared workspaces that include views from multiple tools.

The same design decisions discussed here must also be considered in explicitly creating new multi-user collaboration tools. In particular for some tools, a replication strategy may be desirable while for others the single-server approach is better. Ideally, capabilities for both approaches should be an integral part of the design, achieving both needed performance and reliability, supporting different approaches for different tools. Multiple input streams (with contention) and user-tailored views of shared objects may improve the *look and feel* of many collaborative activities.

6 An overview of H3M – Our wireless architecture

It has been observed that the well-known cellular networks are too rigid and inflexible to adapt to situations in which rapid deployment is critical. Such is the case in disaster-relief, search-and-rescue, law-enforcement, collaborative computing, multimedia classroom, interactive mission planning, and similar special purpose applications. Further, the character of disaster-relief communications is highly variable; i.e., configurations, load (in both type and magnitude), connectivity, and other like parameters, change rapidly. To address the need for self-sufficiency and rapid deployment a number of designs have been suggested including packet radio networks and mobile ad-hoc networks (MANET) [10,11,33,34,40]. While these architectures feature a number of desirable characteristics, they assume that all the hosts in the network are identical in processing and communication capabilities and have difficulty is coping with the dynamics. This, in turn, imposes numerous limitations of these networks both in terms of robustness and overhead in routing messages end-to-end.

In disaster relief operations it is very unlikely that all the hosts are identical [14,15,22,32]. Some hosts may have a wealth of electronic gear connected with their mission; others may have a simple digital-based T/R which provides only simple voice communication. For example, an ambulance or a truck having its own power supply can carry a large amount of sophisticated communication equipment. Naturally, these more powerful hosts could serve as *mobile base stations* (MBS). In this capacity they can serve as cluster heads and also can handle the management activities inherent to the efficient operation of the network. The MBSs are organized into a virtual structure whose actual implementation is adaptive to the availability of assets in the network. Simulation and analysis revealed that H3M is robust, inherently supports multicast, scales well and is well suited for QoS provisioning in high-mobility environments, typical of networks that need to support telemedicine applications in a disaster environment.

In a series of recent papers Foudriat, *et al.* [15-18] proposed a novel high-performance architecture called H3M consisting of a hierarchy of *heterogeneous* hosts distributed over a geographical area and linked together in a wireless communication system. Referring to Figure 5, the lowest level of the hierarchy is the cluster whose connectivity and housekeeping is assumed by a *mobile base station* (MBS, for short). In turn, the MBSs are organized into a virtual network, essentially emulating a local area network-like structure. This is a virtual structure -- the actual implementation depends on the availability of assets in the network. Each cluster supports both inter- and intra-cluster communication

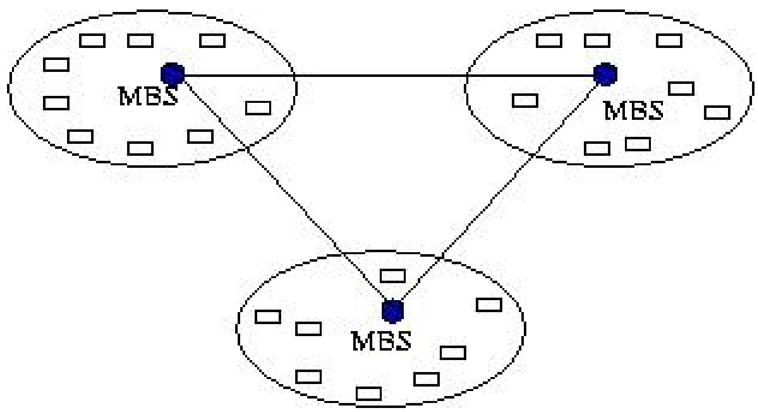


Figure 5: *An H3M network*

In this subsection, we discuss H3M basics, covering features most closely associated with bandwidth utilization and control. A detailed discussion of H3M's protocol activity and operational features can be found in [15-18].

H3M incorporates dynamic, multiple-node, multiple media-access – DMNA – introduced in [15]. All cluster nodes have multiple access within a frame; i.e., each node can send multiple-type messages and submit control information. It differs from other protocols in that it is designed for node decision access as opposed to network-assigned, slotted-message access. Nodes are able to discern sufficient information about link utilization during frame activity in order to cooperate in sharing the link capacity efficiently. This information comes with minimal signalling; hence, minimal use of capacity for control. Hence, nodes are kept current. Using this information, the system supports highly dynamic access and load activity; changes are easily and rapidly accommodated. Hence, network scope decisions can be relegated as needed to support overall cluster activity and therefore can be accomplished at a much slower pace.

DMNA is a framed media-access protocol that supports multiple messaging. Each subframe has dynamic boundaries designed to support a class of message types to be sent efficiently with regard to message dynamics and the total capacity. Knowledge garnered through each subframe use allows the nodes to efficiently utilize subsequent sub-frames. DMNA provides excellent performance with regard to various message types Quality of Service (QoS) needs. Its subframe operation is briefly described in the following subsection

6.1. DMNA protocol operation

The first subframe, the cluster control subframe (CC), provides for the propagation of both cluster and network control information. One node, the cluster leader (CL), updates these parameters including:

- call setup acknowledge and rejection requested by a node in the previous frame,
- node attachment as nodes move and reattach,
- cluster and network activity as clusters are formed and dissolved, and
- bandwidth allocation for this cluster as load balancing is implemented.

Changes relating to this activity are generally at a much slower pace than cluster framing which is typically of the order of 10 msec.

The second subframe frame supports synchronous traffic but in a distinctly different manner from normal Time Division Multiple Access (TDMA). It is designated as the dynamic call node access (DCNA) subframe, i.e., nodes with accepted calls are designed *active*. *Active* nodes employ ordered access i.e., each node knows its order and awaits the silence of the ether from its predecessor node as its cue to begin transmitting. Node capacity needs during a DCNA subframe are variable; i.e., each node is able to submit all its DCNA traffic. This includes any control information such as, new call-setup requests, subsequent subframe needs and all its call information. Calls provide immediate dynamic capacity recovery; if a call is in its silent phase, a minimum size placeholder block is sent. Recovered capacity is available for subsequent subframe use.

The third subframe uses Node Round Robin Reservation Access (NRRRA). *Active* nodes with asynchronous traffic can reserve a slot by signalling their intent in the immediately preceding DCNA subframe. Like the DCNA subframe, ordered access is used. The major justification for implementing the NRRRA subframe is to reduce potential collisions which may occur if all nodes were forced to use the fourth subframe, Carrier Sensed Multiple Access with Collision Detection (CSMA_CD) for all asynchronous traffic. There is no assurance that a node may get message access during the NRRRA subframe if other nodes have sufficient traffic to cause this subframe to overflow its allotted time. In this situation, the next NRRRA subframe is reordered to start at the first node which was denied access.

An inactive node becomes active when it has at least one call or large asynchronous message accepted. When it becomes active, it occupies the last access position in the DCNA and NRRRA subframes. Call acceptance is based strictly on the message's maximum bandwidth and the sum of all other calls presently active. Call acceptance is designed to admit calls so as to not exceed a percentage of a frame's total capacity. Inactive nodes with synchronous and/or large asynchronous messages such as large files; they become active by using a setup packet. Also, nodes using the NRRRA subframe can adjust their allotted time use to improve fairness.

With both DCNA and NRRRA subframe available to active nodes, the CSMA_CD subframe is reserved for inactive nodes, i.e., nodes without call or large data messages. CSMA_CD operates similar to standard Ethernet with collision detection and back-off. Inactive nodes use the CSMA_CD subframe for small data traffic blocks and for signaling to become active.

In summary, DMNA supports a wide range of synchronous (voice, real-time, and video messages types) and asynchronous (large and small data message types) traffic. By enabling access by nodes throughout the frame, transport delay is minimized, message dynamics are efficiently supported, and dynamic capacity recovery and reuse supported. For example in disaster situations, medical video traffic coming on line may instantaneously change a cluster's load significantly. H3M easily and rapidly accommodates this activity. Published results [15-18] demonstrate excellent performance over a wide range of operational conditions.

6.2. Intra- and inter-cluster communications

Nodes form a single cluster for intra-cluster communication. They use a single band. Each node is able to send and receive to its cluster's nodes. At higher bandwidths, the time-delay needed for physically separated nodes to operate when sharing a band using carrier sensing becomes costly. For operations at data rates of 10 Mbps, time-delay limits for node separation are in the order of 1 - 2 km. In wireless networks, a second but less limiting distant factor is node transmitter power. However, battery-operated, hand-held radios perform effectively within the above distance limitation.

H3M inter-cluster communication in a wireless environment is supported by two mutually exclusive factors:

- at least one node in each cluster has sufficient transmitter power to be heard by all other clusters; and
- nodes in each cluster have enough additional receivers so that each cluster can monitor outside cluster messages and retransmit them where necessary.

In some environments such as a wired ether, the first requirement is not necessary since wideband repeaters can be stationed appropriately to maintain signal strength across the network.

The H3M protocol operates with minimal routing – i.e., only the intra-cluster's knowledge of the nodes presently attached to it is needed across the network. Routers are replaced by repeaters. This permits simple, rapid, and dynamic deployment and reconfiguration. It also provides the mechanism by which other protocols can be easily integrate with other protocols as discussed in the next paragraph.

H3Ms ability to integrate and/or support other protocols (ATM, Ethernet, etc.) in a virtually transparent manner is an important feature for disaster relief communications. Reference [13] shows, for example, that H3M is capable of supporting ATM packet transfer both within and through virtually transparently (with the addition of a simple header containing the node addresses). This permits easy connectivity, permitting H3M to replace the communications in the damaged area and operate as a bridge between in-place networks at the edges of the damage area.

A more complete discussion of the need for and availability of heterogeneously equipped nodes needed for H3M can be found in [15-18]. By meeting these operational requirements, H3M provides superior performance features over many wireless protocols related to delay, jitter, routing, multicasting, capacity utilization, dynamic bandwidth recovery, etc.

6.3. Bandwidth reallocation and sharing

Bandwidth management and load balancing are major differentiators of H3M from other protocol approaches. Node movement, cluster use and message load changes can result in congestion in some clusters while others may under-utilize their allocated capacity. A solution to bandwidth utilization to implement load balancing was investigated in DRAMA [27,41]. Here, bandwidth available to the entire network was partitioned into bands. At any time, a cluster managed a number of bands and depending on overall needs was given more bands (or had taken away). This solution required each station to have as many transmitters and receivers as available assignable bands - clearly, not a practical solution. By contrast, the H3M solution uses a single band for each cluster but allows each band to use variable bandwidth.

As in DRAMA, each CL monitors the utilization of all cluster bands and computes the optimal bandwidth assignments. Since all clusters observe the same network, they will come to the same solution. Each cluster will act on this information and, if necessary, change its assigned bandwidth, signal the change in the next or subsequent frames. Although H3M differs markedly from DRAMA, the load-balancing algorithms studied in the latter [27,41] should be readily adaptable to the former situation.

We use Software Radio Technology to enable VFVB T/Rs. We need frequency and bandwidth changes to be made within the order of microseconds, so that changes can be made rapidly and successfully at frame-time intervals. The capability of changing the cluster bandwidth at each frame interval allows for a degree of load balancing QoS which is significantly superior to methods which rely on in- or out-band signaling.

6.4. Specializing H3M to disaster relief

The main goal of this subsection is to point out ways in which the robustness of H3M can be used to provide dedicated functionality in support of disaster management operations as well as other emergency situations.

6.4.1. H3M as the Center of Communications

H3M was designed by interoperability in mind. Indeed, interfacing H3M to the Internet is immediate, with the network leader designating one (or more) of the MBSs as gateways. One of the interesting characteristics of H3M is that it naturally supports Mobile IP. This is due, in part, to the fact that local mobility within H3M can be easily hidden from the outside world. Indeed, each MBS plays the role of point of attachment for the stations in its cluster. Station migration between clusters is not visible from the outside, since only the point of attachment of the station within H3M changes but not the care-of address. Information about the new point of attachment is handled exactly as normal station mobility. For details we refer the reader to [15].

An immediate corollary is that H3M can play the role of the communication center of the disaster management operation. In particular, H3M can perform the following operations provide the interface between wireless sensor networks deployed in the terrain and various authorities including Police HQ, Fire HQ, the Point of Command and Control (PCC), as illustrated in Figure 6 provide the coordination and control functions associated with a mobile task force deployed in support of disaster management, as illustrated in Figure 7.

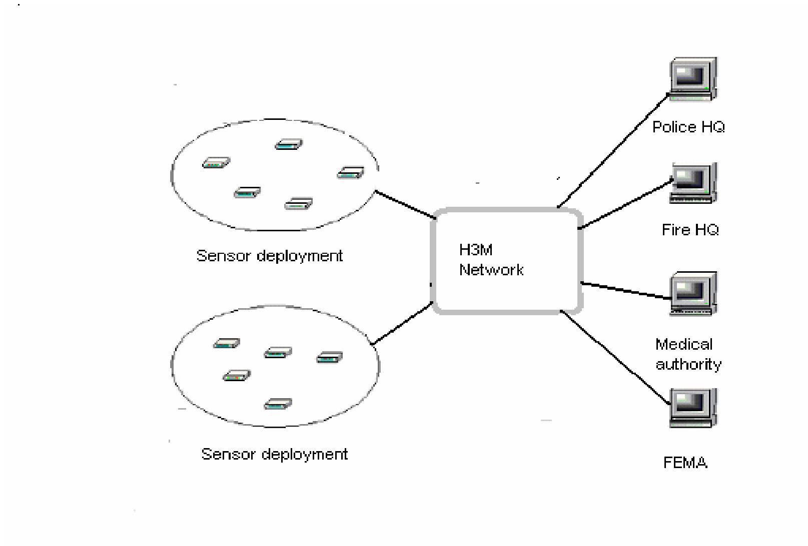


Figure 6: *H3M as the center of communications*

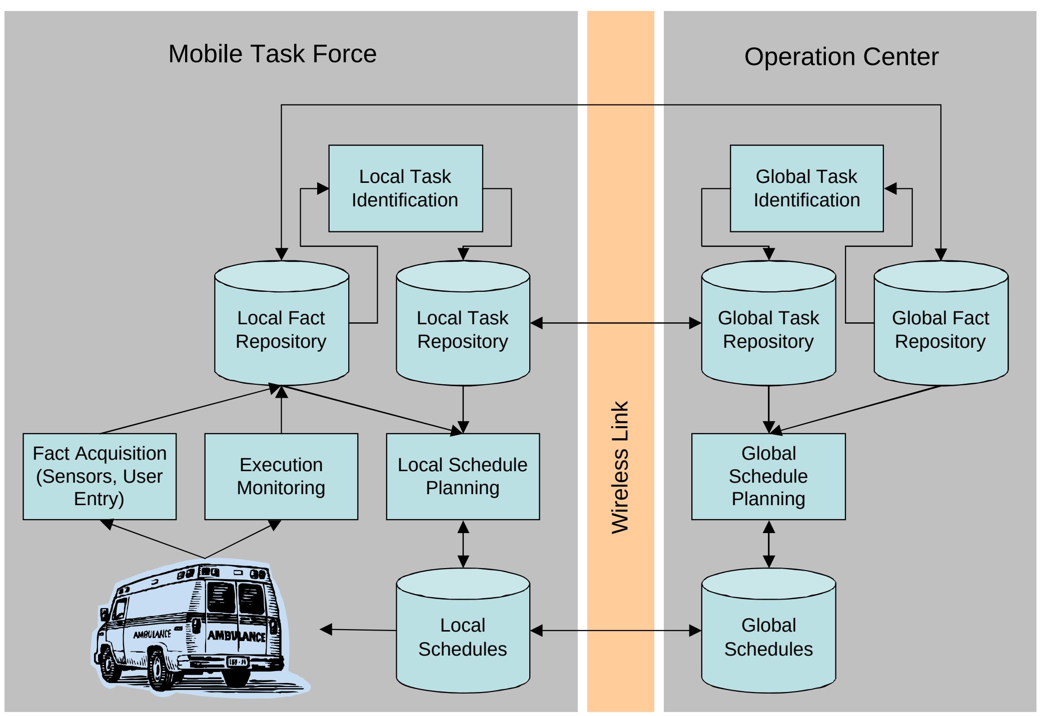


Figure 7: *H3M as the coordinator of the mobile task force*

6.4.2. Location awareness

Location awareness in wireless networks refers to a collection of tasks that, collectively, strive to provide the mobile hosts with the desired degree of geographic location awareness that they need in order to perform their duties. It was realized, quite a while back, that extending emergency 911-like services (E-911) to a continually growing mobile population is one of the extremely important mobility applications. Location awareness is even more important in the context of disaster management where the support personnel is faced with numerous hazards in trying to rescue the victims [5,17,21,22,37].

The bulk of the proposed solutions to emergency location awareness in wireless environments are either reactive in nature or else rely on GPS-enabled end users. While GPS-enables devices will become ubiquitous in the future, at present the use of GPS in highly accurate emergency location management is problematic. For one thing, commercially available GPS-enabled devices do not have the required accuracy to enable pinpointing the exact location of the victims (especially in an urban environment). For another, GPS does not work well in poor atmospheric conditions, the very conditions under which emergency situations are likely to arise.

Recently, Olariu *et al.* [37] proposed a novel, proactive, light-weight, GPS-free solution to providing high quality location management in support of disaster relief operations. Their philosophy is that most of the task of user location is best left to the user itself whose hand-held unit is quite capable of monitoring its location by cleverly exploiting beacons from neighbouring MBSs along its trajectory. The location awareness protocol of [37] is lightweight as it involves overloading slightly currently-performed signalling. In addition, it can be easily incorporated into H3M.

7 Concluding remarks and future work

In 1989, as a result of the massive earthquake that hit the Soviet Republic of Armenia in late 1988, NASA conducted the first international telemedicine program known as *Space Bridge to Armenia/Ufa*. As part of the program, telemedicine consultations were conducted using one-way video, voice, and facsimile between a medical center in Yerevan, Armenia and four medical centers in the U.S. The program was extended to Ufa, Russia to facilitate burn victims after a terrible railway accident. This project demonstrated that medical consultation could be conducted over a satellite network crossing political, cultural, social, and economic borders [53].

Telemedicine, as practiced today, assumes the availability of high-speed, high-bandwidth wired networks and, consequently, near-instantaneous access to all the resources of the Internet. However, such is not the case in a disaster area, where the existing networking and other ancillary infrastructure may no be operational. The net result is that in many situations, present-day telemedicine cannot be delivered when and where its services are desperately needed [54].

A new kind of telemedicine is needed – one that relies on low-bandwidth, rapidly deployable mobile systems that are self-organizing, heterogeneous, and that do not rely on pre-existing infrastructure. It is clear that robust wireless communication systems and avant-garde medical imaging are key enabling technologies that can bring to the scene of the disaster the experience and expertise of medical personnel that can direct and supervise paramedics in providing necessary life-support services. Further, these services must be embedded in a robust, adaptable, interactive portable multimedia delivery system that can adapt to and exploit changing communication capabilities.

The main contribution of this paper was to present a novel system architecture for a Wireless Interactive Remote Medicine (WIRM) system. As such, our main focus is to describe the three aspects of WIRM, namely a novel 3D compression technique using SPS images, an interactive remote visualization tool, and a new wireless network structure that is at the same time rapidly deployable, robust, and can handle multimedia-grade streams.

One of the important benefits of WIRM is the use in search-and-rescue and other disaster-related operations, including high quality rescue service for landmine victims where in most cases it is hard to move the patient and medical personnel with advanced equipment has to operate on scene, hence the need for WIRM as telemedicine platform.

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