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On mixed reality environments for minimally invasive therapy guidance: Systems architecture, successes and challenges in their implementation from laboratory to clinic

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ABSTRACT

Mixed reality environments for medical applications have been explored and developed over the past three decades in an effort to enhance the clinician's view of anatomy and facilitate the performance of minimally invasive procedures. These environments must faithfully represent the real surgical field and require seamless integration of pre- and intra-operative imaging, surgical instrument tracking, and display technology into a common framework centered around and registered to the patient. However, in spite of their reported benefits, few mixed reality environments have been successfully translated into clinical use. Several challenges that contribute to the difficulty in integrating such environments into clinical practice are presented here and discussed in terms of both technical and clinical limitations. This article should raise awareness among both developers and end-users toward facilitating a greater application of such environments in the surgical practice of the future.

1. Introduction

1.1. Virtual, augmented and mixed reality

Multi-modality data visualization has become a focus of research in medicine and surgical technology, toward improved diagnosis, surgical training, planning, and interventional guidance. Various approaches have been explored to alleviate the clinical issues of incomplete visualization of the entire surgical field during minimally invasive procedures by complementing the clinician's visual field with necessary information that facilitates task performance. This technique is known as augmented reality (AR) and it was first defined by Milgram et al. [1], as a technique of "augmenting natural feedback to the operator with simulated cues". This approach allows the integration of supplemental information with the real-world environment.

Augmented environments represent the "more real" subset of mixed reality environments. The latter spans the spectrum of the reality-virtuality continuum (Fig. 1) and integrates information ranging from purely real (i.e. directly observed objects) to purely virtual (i.e. computer graphic representations). The spatial and temporal relationship between the real and virtual components and the real world distinguishes AR environments from virtual reality (VR) environments. A common interpretation of a VR environment is one in which the operator is immersed into a synthetic world consisting of virtual representations of the real world that may or may not represent the properties of the real-world environment [2]. Moreover, both AR and VR environments belong to the larger class identified as mixed reality environments. Mixed realities may include either primarily real information complemented with computer-generated data, or mainly synthetic data augmented with real elements [2,3]. While the former case constitutes a typical AR environment, the latter extends beyond AR into augmented virtuality (AV) [4–6].

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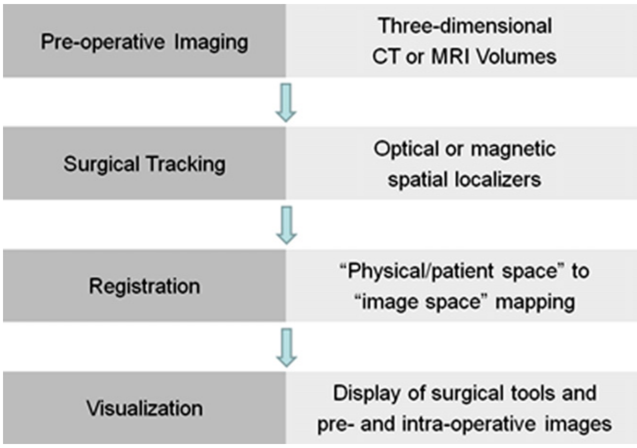

Fig. 1. Components of a mixed reality image guidance process for surgical interventions:pre-operative imaging, surgical instrument localization, data integration, and lastly visualization, information display and surgical navigation.

The first attempt toward augmented reality occurred weeks after Roentgen announced his discovery of X-rays in 1896, when several inventors announced a fluoroscopic device under different names: the "Cryptoscope" by Enrico Salvioni, the "Skiascope" by William Francis Magie, and the "Vitascope" by Thomas Edison. These devices were all described as a "small darkroom adapted to the operator's eyes and fitted with a fluorescent screen" [7]. This device was later referred to as the "Fluoroscope" in the English speaking countries [7], while in the French literature it was called the "Bonnette Radioscopique" [8].

The "more modern" forms of augmented and virtual realities have their beginnings in the 1980s with the development of LCD-based head-mounted displays; the first VR system known as VIVED (virtual visualization environmental display) [9] was developed in 1982; the VIEW (virtual interface environment workstation) system [10] was launched in late 1980s; and one of the pioneer augmented virtuality (AV) systems was introduced in the context of surgery by Paul et al. [11] in the early 2000s.

1.2. Augmented environments in image-guided therapy

The advent of VR and AR environments in the medical world was driven by the need to enhance or enable therapy delivery under limited visualization and restricted access conditions. Computers have become an integral part of medicine: patient records are stored electronically, computer software enables the acquisition, visualization and analysis of medical images, and computer-generated environments enable clinicians to perform procedures that presented difficulties decades ago via new minimally invasive approaches [12,13]. Technological developments and advances in medical therapies have led to the use of less invasive treatment approaches for conditions that require surgery and involve patient trauma and complications.

Medical mixed realities have their beginnings in the 1980s [14,15]. Augmented reality surgical guidance began in neurosurgery in the 1980s with systems incorporated into the operating microscope [16–18]. The first simulated surgery for tendon transplants was published in 1989 and an abdominal surgery simulator was reported in 1991 [19]. Graphical representations of realistic images of the human torso, accompanied by deformable models, and later complemented by more realistic simulations of a variety of medical procedures using the Visible Human Dataset from the National Library of Medicine in 1994 were published in [20,21]. Virtual endoscopy had its beginnings in the mid-1990s and experienced simultaneous developments from several groups; by the late-1990s a wide variety of imaging, advanced visualization, and mixed reality systems were developed and employed in medicine [22]. The MAGI system described the technical stages required to provide AR guidance in the neurosurgical microscope and was one of the first to undergo significant clinical evaluation [23,24]. Today, VR and AR medical environments are employed for diagnosis and treatment planning [25], surgical training [26–30], pre- and intra-operative data visualization [31–34], and for intra-operative navigation [12,35–38].

2. Components and infrastructure

In spite of the wealth of information available due to the advances in medical technology, the extent of diagnostic data readily available to the clinician during therapy is still limited, emphasizing the need for interventional guidance platforms that enable the integration of pre- and intra-operative imaging and surgical navigation into a common environment (Fig. 1).

2.1. Imaging

Minimally invasive interventions benefit from enhanced visualization provided via medical imaging, enabling clinicians to"see" inside the body given the restricted surgical and visual access. Pre-operative images are necessary to understand the patient's anatomy, identify a suitable treatment approach, and prepare a surgical plan. These data are often in the form of high-quality images that provide sufficient contrast between normal and abnormal tissues, along with a representation of the patient that is sufficiently faithful for accurate image guidance [39]. The most common imaging modalities used pre-operatively include computed tomography (CT) and magnetic resonance imaging (MRI).

Since the surgical field cannot be observed directly, intra-operative imaging is critical for visualization. The technology must operate in nearly real time with minimal latency (i.e., that does nor interfere with the normal interventional workflow) to provide accurate guidance, be compatible with standard operating room (OR) equipment, however, at the expense of spatial resolution or image fidelity. Common real-time intra-operative imaging modalities include ultrasound (US) imaging, X-ray fluoroscopy, and more recently, cone-beam CT and intra-operative MRI.

2.1.1. Computed tomography

Computed tomography produces 3D image volumes of tissue electron densities based on the attenuation of X-rays [40]. Conventional multi-detector CT imaging systems are rapidly competing with the latest generation of 320-slice scanners, including the Aquilion™ system from Toshiba [41] and the Brilliance™ iCT system from Philips [42], which can acquire an entire image of the torso in just a few seconds, as well as allowing "cine" imaging and dynamic visualization of the cardiac anatomy.

CT has been employed for both diagnostic imaging [43] and surgical planning [44]. However, classical CT scanners present limited intra-operative use. If used for direct guidance, physicians would need to reach with their hands inside the scanner [45]. This option is not feasible considering the increased radiation dose during prolonged procedures. In addition, since dynamic CT images are acquired in single axial slices, it is difficult to track a catheter or guide-wire that is advanced in the axial direction, as its tip is only visible in the image for a short time. Consequently, CT is more suitable for procedures where the tools are remotely manipulated and in the axial plane [46].

2.1.2. Magnetic resonance imaging

MR images are computed based on the changes in frequency and phase of the precessing hydrogen atoms in the water molecules