Journal of Biomedical Informatics 55 (2015) 124–131

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Development of a surgical navigation system based on augmented reality using an optical see-through head-mounted display

Xiaojun Chen [a],*, Lu Xu [a], Yiping Wang [a], Huixiang Wang [b], Fang Wang [b], Xiangsen Zeng [b], Qiugen Wang [b], Jan Egger [c]

[a] *Institute of Biomedical Manufacturing and Life Quality Engineering, State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China*

[b] *Shanghai First People's Hospital Affiliated to Shanghai Jiao Tong University School of Medicine, Shanghai, China*

[c] *Faculty of Computer Science and Biomedical Engineering, Institute for Computer Graphics and Vision, Graz University of Technology, Graz, Austria*

ARTICLE INFO

Article history:
Received 24 August 2014
Revised 20 March 2015
Accepted 9 April 2015
Available online 13 April 2015

Keywords:
Surgical navigation
Augmented reality
Optical see-through HMD
Intra-operative motion tracking

ABSTRACT

The surgical navigation system has experienced tremendous development over the past decades for minimizing the risks and improving the precision of the surgery. Nowadays, Augmented Reality (AR)-based surgical navigation is a promising technology for clinical applications. In the AR system, virtual and actual reality are mixed, offering real-time, high-quality visualization of an extensive variety of information to the users (Moussa et al., 2012) [1]. For example, virtual anatomical structures such as soft tissues, blood vessels and nerves can be integrated with the real-world scenario in real time. In this study, an AR-based surgical navigation system (AR-SNS) is developed using an optical see-through HMD (head-mounted display), aiming at improving the safety and reliability of the surgery. With the use of this system, including the calibration of instruments, registration, and the calibration of HMD, the 3D virtual critical anatomical structures in the head-mounted display are aligned with the actual structures of patient in real-world scenario during the intra-operative motion tracking process. The accuracy verification experiment demonstrated that the mean distance and angular errors were respectively 0.809 ± 0.05 mm and 1.038° ± 0.05°, which was sufficient to meet the clinical requirements.

1. Introduction

During the past decades, computer-aided navigation system has experienced tremendous development for minimizing the risks and improving the precision of the surgery [2]. Nowadays, some commercially-available surgical navigation systems have already been tested and proved for clinical applications such as eNLight and NavSuite (Stryker Corporation, USA), Portable Nanostation (Praxim, France), and MATRIX POLAR (Scopis medical/XION, Germany). Meanwhile, many research groups also have presented their systems in the literature, for example, TUSS (Queen's University, Canada), VISIT (University of Vienna, Austria), IGOIS (Shanghai Jiao Tong University, China), etc. [3–7]. However, all of these systems use computer screen to render the navigation information such as the real-time position and orientation of the surgical instrument, and virtual path of preoperative surgical planning, so that the surgeons have to switch between the actual operation site and computer screen which is inconvenient and impact the continuity of surgery.

In recent years, due to the great development of Augmented Reality (AR) technology, more and more wearable AR devices have appeared like Google Glass, Skully AR-1 (An AR motorcycle helmet) [8], and etc. AR is an integrated technique of image processing, and in AR system, real objects and virtual (computer-generated) objects are combined in a real environment. Furthermore, real and virtual objects are aligned with each other, and run interactively in real time [1,9,10]. Due to the advantages of AR visualization, developing a surgical navigation system based on AR is a significant challenge for the next generation. For example, after the registration of the preoperative CT in relation to the intra-operative realistic scene, surgeons can superimpose the virtual CT data onto the patient's anatomy [11]. In 2010, Liao et al. [12,13] developed a 3-D augmented reality navigation system for MRI-guided surgery by using auto-stereoscopic images, and the system creates a 3D image, fixed in space, which is independent of viewer pose. In addition, Navab et al. [14] from Technical University of Munich have demonstrated a very practical

---

* Corresponding author at: Room 805, School of Mechanical Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, Minhang District, Shanghai 200240, China. Tel.: +86 13472889728, +86 21 34204851; fax: +86 21 34206847.

E-mail address: xiaojunchen@163.com (X. Chen).

http://dx.doi.org/10.1016/j.jbi.2015.04.003

application of AR. They developed an X-ray C-arm system equipped with a video camera, so that a fused image that combines a direct video view of a patient's elbow with the registered X-ray image of the humerus, radius, and ulna bones was produced.

This study presents an AR-based surgical navigation system (AR-SNS) using an optical see-through HMD (head-mounted display), which encompasses the preoperative surgical planning, registration, and intraoperative tracking. With the aid of AR-SNS, the surgeon wearing the HMD can obtain a fused image that virtual anatomical structures such as soft tissues, blood vessels and nerves integrated with the intra-operative real-world scenario, so that the safety and reliability of the surgery can be improved.

2. Materials and methods

2.1. The hardware architecture of AR-SNS

The AR-SNS is constructed based on a high-performance graphical workstation (HP), a 2D LCD monitor (G2200W, BenQ), an optical tracking device (Polaris Vicra, NDI Inc., Canada) and an optical see-through HMD (nVisor ST60, NVIS, United States) (Shown in Fig. 1). The workstation is equipped with a 4 GB memory card, a core i7 CPU and an nVIDIA Quadro FX4800 graphic card, running on the windows 7 operating system. As for HMD, it uses high-resolution microdisplays featuring 1280 × 1024 24-bit color pixels per eye, for vivid visual rendering and integration with reality.

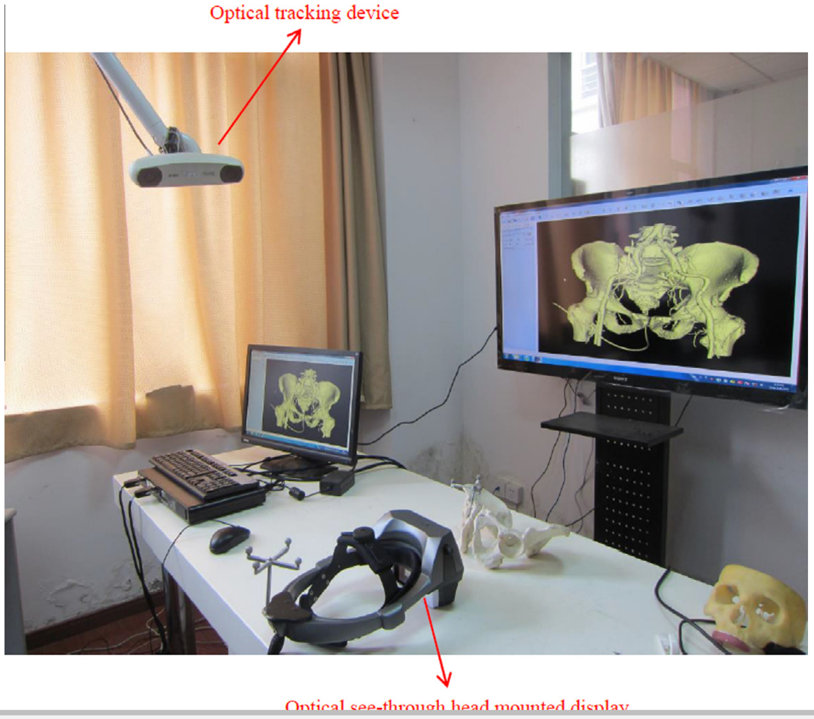
2.2. The software framework of AR-SNS

The AR-SNS is developed under the platform of the Integrated Development Environment (IDE) of VS2008. All of the functions are programmed in Microsoft Visual C++ and some famous toolkits are also involved, such as the Visualization Toolkit (VTK, an open source, freely available software system for 3D computer graphics, image processing, and visualization etc., http://www.vtk.org/), CTK, ITK, IGSTK and QT, and then integrated into the AR-SNS.

Fig. 2 shows the framework of AR-SNS, and is described as follows: on the basis of the preoperative CT data of a patient, image segmentation is conducted, so that 3D models including hard and soft tissues, especially critical anatomical structures such as blood vessels and nerves can be reconstructed. After 3D reconstruction, preoperative planning is implemented so that an optimized osteotomy trajectory can be obtained. Then, with the support of the optical tracking device, the calibration of the surgical instruments is performed, and the point-to-point registration [15–17] and surface matching [18,19] methods are used to determine the spatial relationship between virtual coordinate system (VCS, refers to the computer screen coordinate system) and real coordinate system (RCS, refers to the patient coordinate system) [2]. In addition, an optical see-through head-mounted display is adopted so that an immersive augmented reality environment can be obtained and the virtual tissue can be integrated with the direct view. Finally, after calibration of the patient's position in relation to the HMD, the position and orientation of the virtual model will change with corresponds to the movement of HMD and patient, and match the real anatomical structures during intra-operative navigation process, so that the preoperative plan rendered in HMD can be transferred to the real operation site.

2.3. 3D-reconstruction and preoperative surgical planning

Based on the original CT data, the segmentation of the hard tissue is conducted by using a threshold and region growing combined method, and for the soft tissue in each image, semi-automatic region growing method is adopted, and if it is over-segmented or under-segmented, manual modification is also used. Then, 3D surface models can be reconstructed through the marching cubes algorithm [20]. Fig. 3 shows a 3D pelvis model and a bladder imported into AR-SNS after the 3D-reconstruction. All of the work including the image segmentation and 3D modeling is realized.



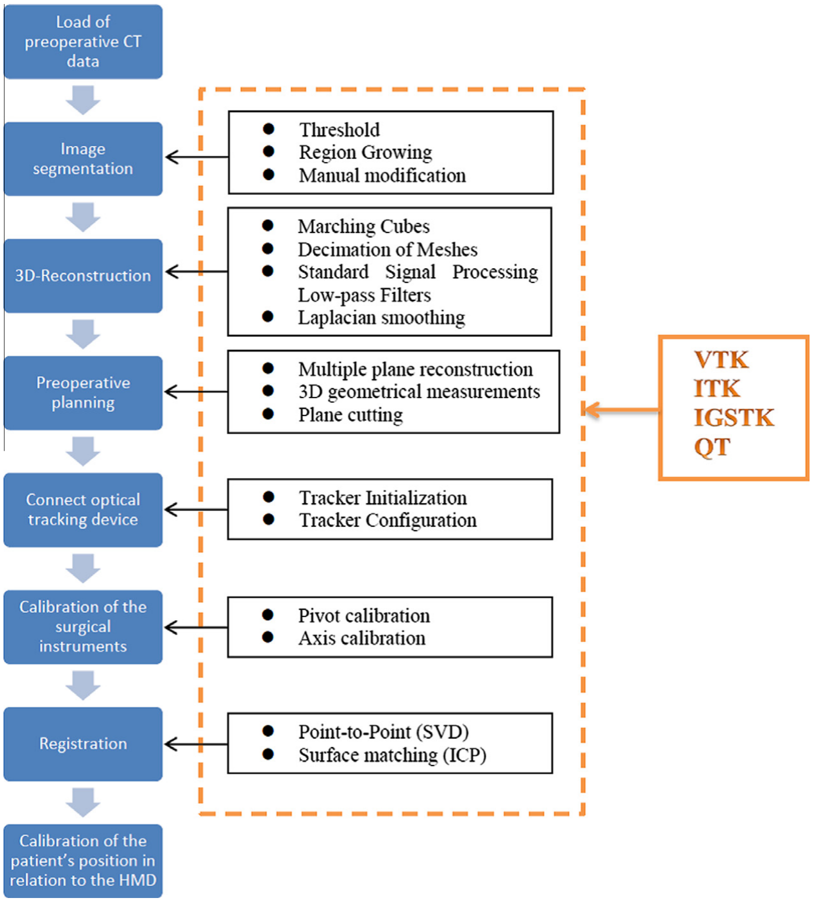


Fig. 2. The framework of AR-SNS.

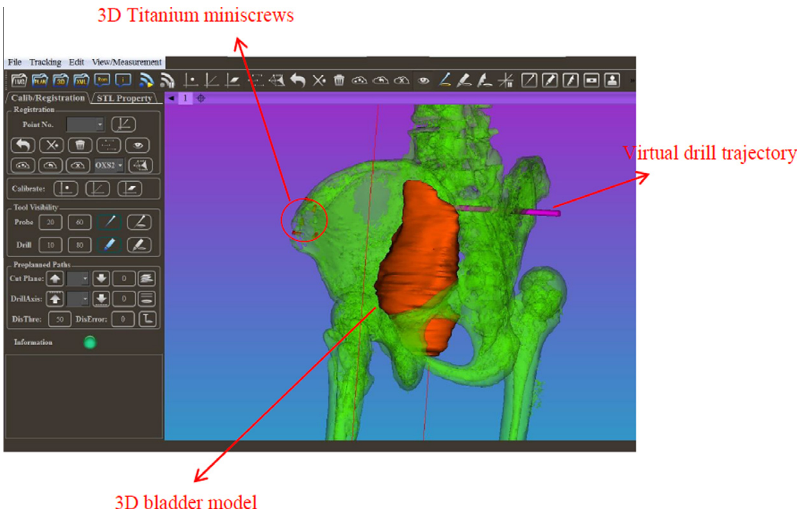


Fig. 3. A 3D pelvis model and a bladder imported into the AR-SNS.

On the basis of these CT images and the 3D model, the procedure of preoperative planning can be implemented and is describe as follows: percutaneous implantation of sacroiliac joint screw is a very common surgery in orthopedics. And, in order to avoid injuring the important anatomical structures like soft tissues, blood vessels and nerves, a virtual path for the surgical drill should be

precision, safety and reliability of the implant surgery can be enhanced.

2.4. Registration

Since the Polaris Vicra optical tracking device only localizes the

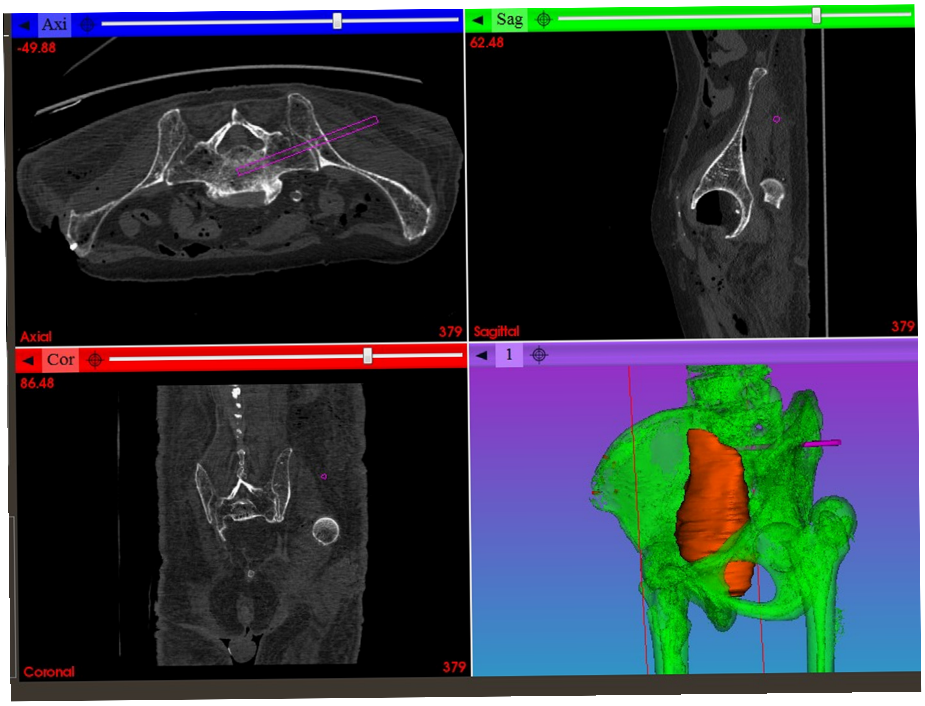


Fig. 4. A virtual path for the surgical drill rendering on all of the 2D/3D views.

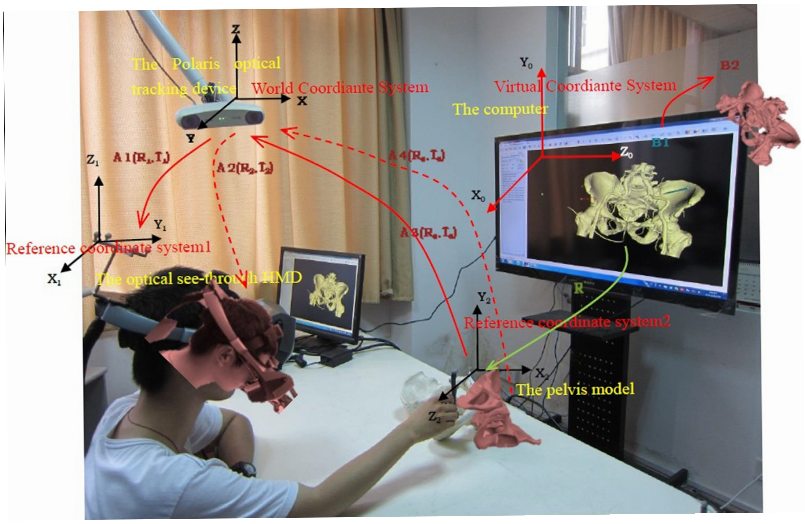


Fig. 5. The establishment of coordinate systems in AR-SNS.

instrument and the mounted reference frame (this procedure is also named as 'calibration') needs to be done first, so that the movements of the reference frame can represent those of the surgical instrument [21]. In AR-SNS, the pivot calibration approach is adopted and the Image-Guided Surgery Toolkit (IGSTK, an open-source C++ software library) provides classes for performing it [22], detailed principle of this calibration, please refer to Ref. [21].

The procedure of registration is an essential component for all computer-aided navigation systems, which brings two coordinate systems into spatial alignment [23]. In this study, the coordinate systems in AR-SNS are established in Fig. 5, and the VCS must be registered (aligned) with the reference frame coordinate system2 (also referred to as the patient coordinate system). A variety of reg- the fiducial point registration and surface registration together so that the registration accuracy is higher than traditional methods. As for the detailed description of the involved algorithms during this procedure, please refer to Ref. [2].

2.5. Calibration of the patient's position in relation to the HMD

After registration, the preoperative images in HMD are aligned with the patient on the procedure table. Then, the calibration of HMD needs to be done. In the AR-SNS, the basic requirement is the calibration of the patient's position in relation to the HMD, which means the movement of the patient or the HMD will not affect the initial correspondence of VCS and RCS. The principle is the calibration matrix after the initial registration of the patient's position in relation to the image data set, we built the transformation relationship shown in Fig. 5. Suppose:

R is the initial transformation matrix of VCS to reference frame coordinate system2;
A_1 and A_2 are respectively the transformation matrix of reference frame coordinate system1 to the World Coordinate System before and after movement of the user head;
A_3 and A_4 are respectively the transformation matrix of reference frame coordinate system2 to the World Coordinate System before and after movement of the patient;
B_1 is the matrix of virtual model under the VCS before movement;
B_2 is the calibration transformation matrix of virtual model under the VCS;

Since the relative position of one point on the computer virtual image is fixed before and after movement, setting X as the coordinate of this point in computer virtual image coordinate system. Then, X_1 is the coordinate of X in VCS (also referred as the computer screen coordinate system) before movement and X_2 is the coordinate of X in VCS after movement. Eq. (1) and Eq. (2) demonstrate the transformational relation:

$$RB_1X = X_1 \tag{1}$$

$$RB_2X = X_2 \tag{2}$$

The purpose is to maintain the relative position of this point in patient coordinate system unchanged before and after movement, so setting X_3 as the coordinate of X in reference frame coordinate system2. Eqs. (3) and (4) show the transformational relation before and after movement:

$$(A_3)^{-1}A_1X_1 = X_3 \tag{3}$$

$$(A_4)^{-1}A_2X_2 = X_3 \tag{4}$$

Thus, based on Eqs. (1)–(4):

$$B_2 = \left[(A_4)^{-1}A_2R\right]^{-1}(A_3)^{-1}A_1RB_1 \tag{5}$$

In the polaris optical tracking system, seven elements representing the unit quaternion and the translation vector, are used to describe the transformation of a rigid body under world coordinate system. Therefore, A_1, A_2, A_3, and A_4 can be calculated on the basis of each rigid body's seven elements provided by the Polaris, and R can be calculated through the point-based registration and surface registration respectively under patient coordinate system and virtual coordinate system.

Since A_1, A_2, A_3, A_4, R, B_1 (which can be supposed as an identity matrix) are all known, the calibration transformation matrix B_2 can be calculated according to Eq. (5). As a result, the position and orientation of the virtual model will change with corresponds to the movement of HMD and patient, and match the real anatomical structures during intra-operative navigation procedure.

The setup of the AR-SNS and the actual view seen from the HMD is also illustrated in Fig. 6.

3. The accuracy verification of AR-based surgical navigation system

The basic aim of using a surgical navigation system is to improve the surgical precision and prevent the intra-operative possible human errors. Therefore, the accuracy verification exper-

which includes three components: a metal base, an organic glass substrate and a 3D-printed cranio-maxillofacial model. The design and manufacturing of the verification block is described as follows:

Based on the original CT scanning data of a volunteer, the virtual cranio-maxillofacial model was 3D reconstructed and assembled with the virtual metal base model using the UG software. Then, according to these data, the real nylon cranio-maxillofacial model was 3D printed using the high precision (0.1 mm) thermoplastics laser-sintering system (EOSINT P 395, Germany). The metal base was manufactured using the advanced 5-axis machine tool (DMU60, Germany) with the overall precision of 0.01 mm, and there were 175 taper holes (Diameter: 5 mm) and 40 through holes (Diameter: 4.2 mm) on its surface for measuring the distance error and angular error respectively.

3.1. The scheme of precision verification experiment

The precision verification process includes all procedures during the AR-based navigation surgery, for instance, CT scanning, 3D reconstruction, calibration of surgical instruments, registration, calibration of head-mounted display, real-time motion tracking, etc. The details are described as follows:

1. Mounting the reference frame on the metal verification block so that it can be tracked by the NDI Polaris Vicra tracking device.
2. Calibrating the positioning probe ("Pivot Calibration" and "Axis Calibration") through the calibration tool. Then, 5 or 6 fiducial landmarks can be collected on the surface of metal base and registered with the matched points on the virtual 3D model.
3. On the basis of the point-based registration, the point cloud can be collected on the surface of 3D printing model to implement the surface-based registration so that the registration errors can be corrected.
4. Calibrating the optical see-through head-mounted display when the user is wearing it. As a result, the 3D models are aligned with the real objects in the HMD during the intra-operative motion tracking process (see Fig. 8).
5. Using the probe to pick 100 target points in different regions of the metal base surface successively, and recording the actual coordinate of each point P_i (P_{ix}, P_{iy}, P_{iz}). Then, the actual coordinate is calculated with the theoretical coordinate of each point P_i^* (P_{ix}^*, P_{iy}^*, P_{iz}^*) to obtain the distance error P_{ierr}

$$P_{ierr} = \sqrt{\left(P_{ix} - P_{ix}^*\right)^2 + \left(P_{iy} - P_{iy}^*\right)^2 + \left(P_{iz} - P_{iz}^*\right)^2}, \quad (i = 0, 1, 2, \ldots, 99) \tag{6}$$

6. Inserting the probe into the 30 axial holes, and recording the actual axial direction A_i (A_{ix}, A_{iy}, A_{iz}). Then, the actual axial direction is calculated with the theoretical axial direction A_i^* (A_{ix}^*, A_{iy}^*, A_{iz}^*) to obtain the angular error A_{ierr}

$$A_{ierr} = \cos^{-1}\left[\left(A_{ix}\cdot A_{ix}^* + A_{iy}\cdot A_{iy}^* + A_{iz}\cdot A_{iz}^*\right)\Big/\left(\sqrt{A_{ix}^2 + A_{iy}^2 + A_{iz}^2} \times \sqrt{A_{ix}^{*2} + A_{iy}^{*2} + A_{iz}^{*2}}\right)\right], (i = 0, 1, 2, \ldots, 29) \tag{7}$$

3.2. The results of the accuracy verification experiment

Before the experiment, the all 175 fiducial landmarks and 40 axial holes on the metal verification block surface were, respectively, divided into different regions (see Fig. 7).

Then, after the optical see-through head-mounted display was calibrated, we measured 100 target points and 30 axial holes in dif-

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**