New Opportunities for Micro Actuators

Hiroyuki Fujita and Kaigham J. Gabriel*

Institute of Industrial Science, The University of Tokyo
7-22-1 Roppongi, Minatoku
Tokyo 106 Japan

*AT&T Bell Laboratories
Holmdel, NJ 07733 U.S.A.

ABSTRACT

Microactuators fabricated by IC-based micromachining technique are reviewed. The microactuators are driven by various forces suitable in the micro domain. The advantages and the limitations of fabrication processes suggest that micro electro mechanical systems (MEMS) in which microactuators plays a key role would be completely different from simple miniaturization of macro machines. A possible architecture oriented to MEMS is a system composed of many smart micromodules; each module having a microactuator, sensors and electrical circuits integrated in itself. As an example, a ciliary motion system and its actuators are explained. Promising applications of MEMS in the near future seem to be in optics, magnetic and optical heads, fluidics, handling cells and macro molecules, and microscopy with microprobes such as STMs (scanning tunneling microscopes) and AFMs (atomic force microscopes).

1. INTRODUCTION

Stimulated by the success in micro mechanical elements[1,2] and electrostatic micro motors[3,4], expectations for making micro electro mechanical systems(MEMS) are emerging rapidly everywhere. It should be noted that Science Fiction dreams such as the micro submarine in the movie "A Fantastic Voyage" are not necessarily the goal of the research. If you think of conventional machines, the three dimensional structure assembled in various shapes is tightly associated with its function. The limitation of typical fabrication process for MEMS only allows us to make planar structures or a projected image of 2-dimensional mask patterns in deep resist[5,6]. However the advantages that many structures can be obtained simultaneously by pre-assembled and batch process and that the integration with electronic circuits and sensors is possible must be fully taken. Therefore, it is most likely that the architecture for the MEMS is completely different from the simple miniaturization of macro machines. Future shapes of the MEMS can be a system composed of 2-dimensionally distributed micromodules[7] or fixed on the tip area of a needle. The development of microactuators must be consistent with the architecture. At least the fabrication process must be compatible with IC-processes[8]. Please note it doesn't necessarily mean microactuators are fabricated only by the IC-process.

This paper consists of three parts; the first part is for various microactuators, the second for one example of the architecture for MEMS and the third for possible applications.

2. MICROACTUATORS

Because of the scaling consideration[9,10] the electromagnetic force which is most commonly used in the macro actuators is not suitable for microactuators. Although some trials were reported on magnetic actuators[11], many microactuators made by micromachining utilizes other driving principles such as the electrostatic force. Table 1 summarizes recent examples of microactuators. Because of limited space, the table is not all inclusive.

2.1 Electrostatic micromotors

In the first row is an electrostatic micromotor with diameters of 60-120 μm by Tai, et al [4]. It is called a side-drive type motor, since it utilizes the electrostatic force which acts between the edges of the rotor and the stator. The rotor and stators are made of polysilicon films, 2 μm thick. Stators are placed on a circle and connected in three phases. If the voltage is applied to each phase successively, the rotor rotates in synchronization. The voltage is up to 300 V across the 1-2 μm gap. The torque is estimated to be a few pNm. Rotational speed was reported to be on the order of 500 rpm. The speed is relatively low compared to the theoretical value[25]. The reason is the friction between the rotor and the shaft, although a silicon nitride film was deposited on the sliding surface to reduce the friction.

In the second row is the improved version of the side-drive micro motor reported by Mehregany, et al.[12]. By improving the design, the fabrication process, and the operating condition of the motor, they achieved the rotational speeds up to 15,000 rpm and continuous operation for more than a week. They reduced the clearance between the rotor and the shaft, formed three dimples under the rotor for both support and electrical contact and operated in nitrogen to avoid oxidation.

2.2 Utilization of Rolling Motion

Even for the improved micromotors, friction is a major problem. One solution is to replace the sliding contact at the center with rolling contact. Mehregany, et al.[12] also made this type of the micromotor. As schematically shown in Fig. 1(a), the rotor is a smooth ring whose inner diameter is only a little larger than the shaft. When the voltage is applied sequentially to stators as shown in Fig. 1(b), the rotor rotates eccentrically without slipping at the contact. Since the circumferential distance of the rotor hole is slightly longer than that of the shaft, the rotor really revolves a fraction of a circle after one eccentric rotation (Fig. 1(c)). This results in two advantages of the motor, e.g. reduction of friction and higher torque at low speed. The usage of rolling motion in microactuators was reported previously by Jacobsen, et al.[26], Trimmer, et al.[27] and the author, et al.[28,29], although fabrication processes for these actuators were not IC based or fully IC-compatible.

91CH2817-5/91/0000-0014$01.00

Table 1. Micro Actuators (fully or partly IC-processed)

driving priciple	size	movement, application	support	speed, response	force, torque	material	input	ref. & authors
1. electrostatic	60～120μm (diameter)	rotation	sliding	500rpm	a few pNm	poly-Si	60～400V	[4]Y. C. Tai, et al.
2. electrostatic	100μm (diameter)	rotation	sliding	15000rpm	10pNm	poly-Si	50～300V	[12]M. Mehregany, et al.
3. electrostatic	100μm (diameter)	rotation	rotation	300rpm	～1nNm	poly-Si	26～105V	[12]M. Mehregany, et al.
4. electrostatic	5x100x100 μm^3	10μm (L. L.)	elastic	10～100kHz (resonance)	2μN	poly-Si	$40V_{DC}$ $+10V_{AC}$	[13]W. C. Tang, et al.
5. electrostatic	4x400x400 μm^3	7μm (L. L.)	elastic	～3kHz (resonance)	0.8μN	poly-Si	10V	[14]T. Hirano, et al.
6. electrostatic	10x500x500 μm^3	2μm (L. L.)	elastic	N. A.	N. A.	poly-imide metal	200V	[15]R. Mahadevan, et al.
7. electrostatic	0.1x0.35 x0.39mm^3	on-off valve	elastic	N. A.	110mmHg	metal, Si_3N_4	30V	[16]T. Ohnstein, et al.
8. electrostatic	4x300x300 μm^3	5μm (L. L.)	elastic	8kHz (resonance)	5μN	poly-Si	19V	[17]N. Takeshima, et al.
9. piezoelectric	8μmx0.2mm x1mm	7μm, STM scan	elastic	N. A.	23μN	ZnO	30V	[18]S. Akamine, et al.
10. piezoelectric	2mm (diameter)	rotation	vibration	100-300rpm	25pNm	PZT	4V (100kHz)	[19]K. R. Udagakumar, et al.
11. shape memory alloy	2x30x2000 μm^3	a few μm	elastic	20Hz	N. A.	TiNi	2mA, 40V	[20]J. A. Walker, et al.
12. thermal	0.5x3x3mm^3	45μm (L. V.)	elastic	～5ms	0.6N	Si+ liquid	～200mV	[21]M. J. Zdeblik, et al.
13. thermal	0.5x8x8mm^3	23μm (L. V.)	elastic	>1Hz	0.1N	Si	13V	[22]F. C. van de Pol, et al.
14. thermal	6x100x500 μm^3	74μm (bending)	elastic	10Hz (square wave)	N. A.	Si+Au	130mW	[23]W. Riethmuller, et al.
15. thermal	5x110x500 μm^3	120μm (bending)	elastic	8Hz(sinusoidal wave)	N. A.	poly-imide	30mW	[7]N. Takeshima, et al.
16. electromagnetic	1.5x5.8 x5.8mm^3	70μm (L. V.)	elastic (L. V.)	94Hz (resonance)	450μN	Au, NdFeB	0.3A	[11]B. Wagner, et al.
17. electromagnetic	0.1x10x10 mm^3	5mm (L. L.)	levitation (Meissner effect)	20mm/s	30μN	YBaCuO, NdFeB	0.3～0.9A	[24]Y. K. Kim, et al.

*L. V.: linear motion in vertical direction, L. L.: linear motion in lateral direction.

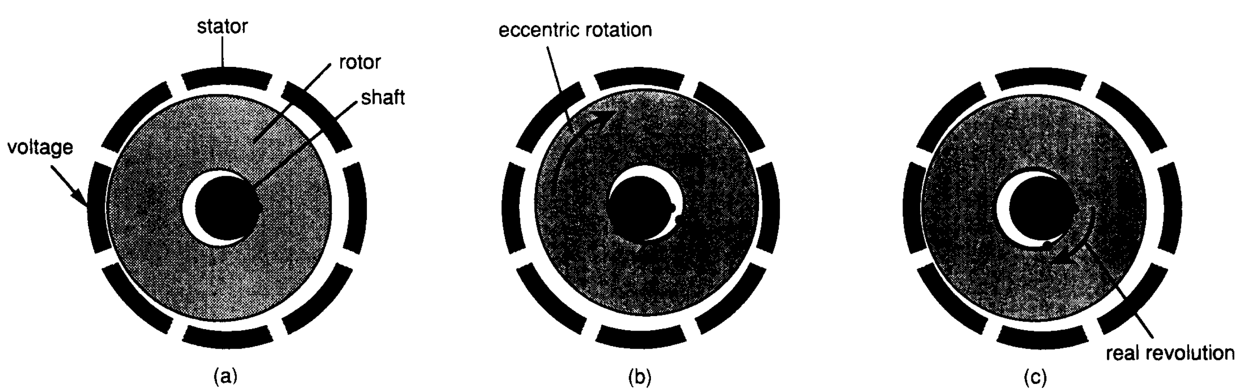

Fig. 1 Operation of a harmonic micromotor [12]

2.3 Elastically Supported Actuators

Another way to avoid the effects of friction is with elastic supports. Five electrostatic actuators with elastic supports are shown in the fourth through the eighth rows. First is an electrostatic resonator by Tang, et al. [13]. The resonator is supported by double-fold beams and actuated by comb-like structures. The teeth of the comb, attached to the moving part, overlap those fixed on the substrate. The force to increase the overlapping is generated when voltage is applied between the two combs. An alternating voltage of 10 V with a 40 V DC bias made the suspended part vibrate at resonance. The displacement was 10 μm and the resonant frequency was 18 kHz with 200 μm-long supports.

Furuhata, et al.[30] introduced the oxidation machining technique to obtain sub-micron operational gaps between moving and driving electrodes. The reduced gap enabled them to operate the modified comb-drive actuator with lower votages that are commonly available in electronic circuits. Hirano, et al.[14] succeeded in obtaining non resonant deflections of 7 μm with 10 V. The overall shape and the device in operation are shown in Fig. 2.

Mahadevan, et al. [15] reported a linear actuator made by polyimide. The mover is a polyimide ladder-like structure sandwiched by two driving electrodes. The electrodes are also patterned in stripes which have the same pitch of the mover but are divided into some sections with different phase shifts. The mover is supported by four polyimide beams. Although the mover is not conductive, it is attracted in between the electrodes which make up a parallel-plate-capacitor. The actuator is interesting because it utilizes the force acting on both surfaces of the mover rather than on the edge.

In the eighth row, an electrostatic valve is shown. A plate with one side fixed is driven electrostatically and seals an inlet orifice. The closure plate is composed of a metal electrode sandwiched by silicon nitride films. The valves are fabricated in a 5 by 5 aray, which results in larger flow rate and finer flow control just by closing some of the valves. It was possible to close the valve against pressures of up to 110 mmHg with 30 V applied to the valve.

2.4 Other Driving Principles

Microactuators which utilizes other driving principles such as piezo electric[18,19], shape memory alloys[20], thermal expansion[7,21-23] and electomagnetic[11,24] are included in Table 1 for comparison. In terms of reducing friction, most of them moves elastically with two exceptions. Udayakumar,[19] et al. made the ultrasonic micromotor which utilizes the standing wave to rotate the rotor. Similar trial was made in the linear motion previously by R.M. Moroney, et al.[31]. Kim, et al.[24] levitated the permanent-magnet mover by the Meissner effect of the superconducting material.

Each actuator in the table has its own advantages and disadvantages. The choice and the optimization should be made according to the requirements of applications. Generally speaking, the electrostatic actuator is more suitable to perform tasks which can be completed within a chip (positioning of devices/heads/probes, sensors with servo feedback, light deflection, etc.), since it is easily integrated on a chip, easily controlled and consumes little power. On the contrary, the other types of actuators are more robust, produce large force and are suitable to perform external tasks (propulsion, manipulation of objects, etc.).

3. ARCHITECTURE FOR MEMS

3.1 System with Micro Smart Modules

An example of system architectures oriented to MEMS is shown in this chapter. As was mentioned above, one of the advantages of MEMS is that many actuators and sensors are supplied with batch processing techniques. Another advantage is that both logic circuits and sensors can be added into the same system. We can expect to have a module which includes sensors, actuators and logic circuits and has primary information processing and control. Furthermore, many of the modules can be implemented in a small area without assembly.

As MEMS, we expect microsystems to perform complicated tasks, such as micromanipulators and self-propelled systems. For example, when a microsystem handles cells, the system must move to the cells by itself and manipulate them. The modules, which have not only actuators but also logic circuits and sensors, can fulfill the requirement. Many modules can be composed and be distributed by taking the advantages of the micromachining. These modules are smart enough to perform elementary control and complex motions with simple input signals. When many modules are arranged on the surface of objects, the surface may be able to perform some functions.

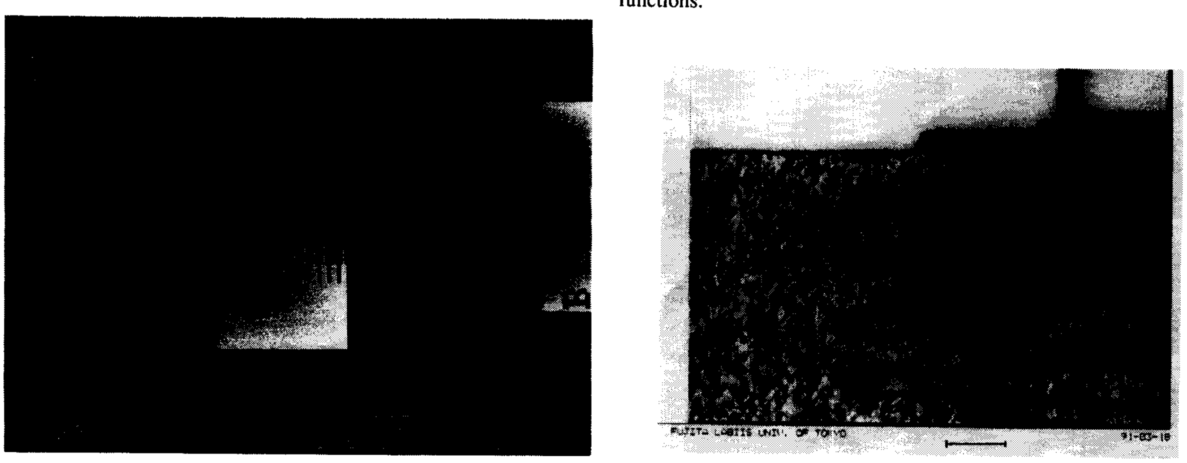

Fig. 2 An electrostatic actuator with sub-micron gaps [14]. (a) Over all view. A comb-like driver, four positioning and alignment mechanisms, and flexible supports are shown. (b) Expanded view of working teeth with 0.5 μm operational gaps.

The system of the organisms offer good models when we want to design the architecture of the systems with distributed modules. Mechanism in organs of animals, insects and microscopic organisms help us to have innovative ideas. The ciliary motion is based on the motion of ciliate. The ciliate, one of microscopic organisms, has many hairlike protrusions on the surface of its cells. The protrusions are called cilia. It accomplishes locomotion by vibrating cilia cooperatively. The motion of the ciliate can be applied to convey objects. The modules of the ciliary motion system are compromised of an actuator (such as a cantilever type actuator) and a self-excited vibrations circuit as shown in Fig.3. Adequate interconnection and external signals can synchronize frequencies of the vibration. When the fixed phase difference between adjacent vibrations is uniformaly maintained, each actuator runs cooperatively. Cantilevers propagate a wave and carry objects like balls. When a plate is carried, required logic circuits are as simple as shift registers. This system is a one-dimensional system and is composed of exactly the same modules. The motions of actuators in the modules are very simple and can be easily realized by microactuators.

3.2 Ciliary Motion System

The ciliary motion system realized by combining cantilevers and logic circuits as shown in Fig.4[7]. In the following, only the microactuator for ciliary motion module is considered. Benecke and Riethmuller have made a composite cantilever based on thermal expansion effects with gold and silicon like a bimetallic cantilever[16]. They also proposed a similar transportation system based on cantilever actuators[32].

The present actuator[17] consists of a metal micro heaters, sandwiched by two layers of polyimide which have different thermal, a expansion coefficient. The cantilever curled upward at room temperature as shown in Fig. 5 because of the tensile stress building up after curing polyimide at elevated temperatures. When the cantilever was heated by flowing current in the heater, it moved downwards. The dimensions of the cantilever are 500 µm in length, 110 µm in width, 2.2 µm in the thickness of the lower polyimide layer with small thermal expansion, and 3.6 µm in the thickness of the upper polyimide layer with large thermal expansion. Vertical displacements of 130 µm and horizontal displacements of 60 µm were obtained with 40 mA drive curent in the heater. The actuator band width (3 dB down in displacement amplitude) was measured to be 8 Hz. Eight cantilevers in two units moved cooperatively. Future developments to combine logic circuits are envisioned.

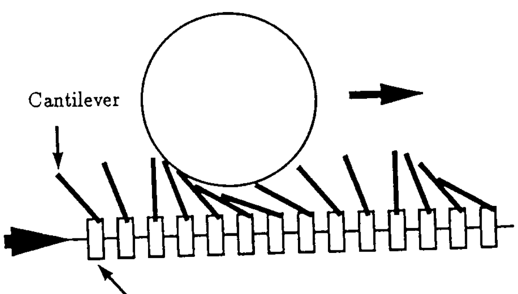

Fig. 3 Ciliary motion system [7].

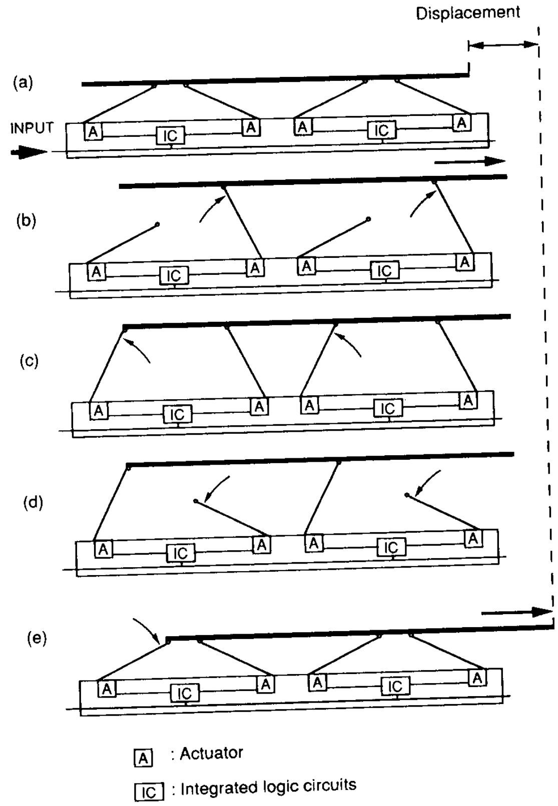

Fig. 4 Diagram of a ciliary system [7].

Fig. 5 SEM photograph of polyimide thermal actuators [7]. The size is 500 µm x 110 µm. Cantilevers curl up at the room temperature due to intentionally introduced residual stress.

4. APPLICATIONS

Figure 6 shows possible applications of microactuators and MEMS. Promising applications in the near future are in optics, magnetic and optical heads, fluidics, handling cells and macro molecules, and microscopy with microprobes such as STMs (scanning tunneling microscopes) and AFMs (atomic force microscopes)[18]. These applications have a common feature that only very light objects such as mirrors, heads, valves, cells and microprobes are manipulated and that little physical interaction with the external environment is necessary. One reason is that present microactuators are still primitive and large forces cannot be transmitted to the external world. The other reason is difficulty in packaging. In the following, a few examples are explained.

4.1 Optics

Petersen, et al.[18] demonstrated deflecting light beams by small cantilevers driven by electrostatic force in 1977. The dimensions of the cantilever were 100 μm in length, 25 μm in width and 0.5 μm in thickness. Recently, an optical-fiber switch[34], its aligner[35] and an adjustable miniature Fabry-Perot interferometer[36] were reported. Sawada, et al[37] developed a new integrated optical microencoder. They integrated a U-shaped laser diode with etched mirrors, microlenses and a photodiode. The size was 0.5 X 0.5 mm^2 square. They claimed a theoretical resolution of 0.01 μm with a 1 μm-pitch grating. Because of its size and the fabrication process, it is possible to integrate the encoder with microactuators, that will result in a micro positioner with very high accuracy.

4.2 Fluidics

Good review articles [38,39] were already published on micro fluidic systems. Here only the application to the ink jet printer is dealt. Using silicon micromachining and bonding techniques, Shibata, et al.[40] fabricated micro nozzles and attached a micro heater to each channel. When the pulse current flows in the heater, the ink turns into the supercritical state locally around the heater and shoots a droplet out from the nozzle. Although there is nothing to move, the heater acts as a microactuator. The printer utilizes the principle, called *a bubble jet printer*, has been commercialized and proved to be successful.

4.3 Micro Magnetic Head

Micro sliders for read-out can be fabricated by IC-compatible processes. Let us examine the micro system in which the slider is attached to micro flextures and driven by microactuators [41,42]. The purposes of the motion are to compensate tracking errors and to avoid crashing. Although large movement such as seeking has to be done by macro structures and actuators, these functions can be miniaturized because of the lighter load. Since the range of movement is limited, the flexible support eliminates friction. Response frequency should be in the order of 10 kHz. If the micro slider is small enough, improved electrostatic actuators will be applicable. Assembly and adjustment are minimized by the pre-assembly capability of micromachining. Small signals associated with the miniaturized head should be amplified by the pre-amplifier located on the same chip. A displacement sensor to detect the gap

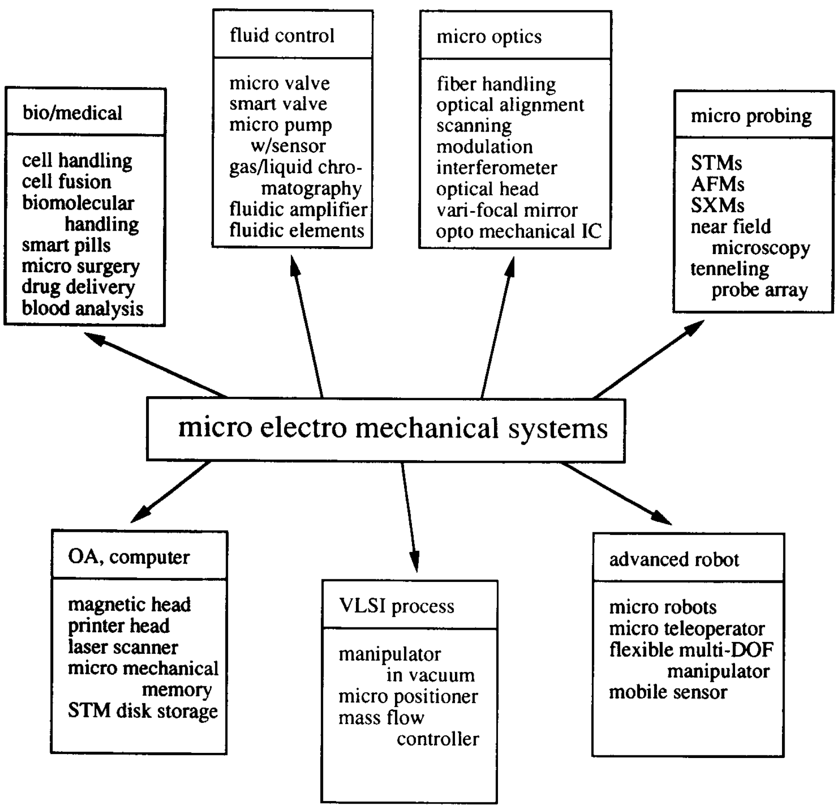

Fig. 6 Possible applications of micro electro mechanical systems

DOCKET ALARM

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

fastcase®
Smarter legal research.