specialised imaging

Research Article

Dissecting Time...
A review of the development of ultra high-speed imaging techniques.

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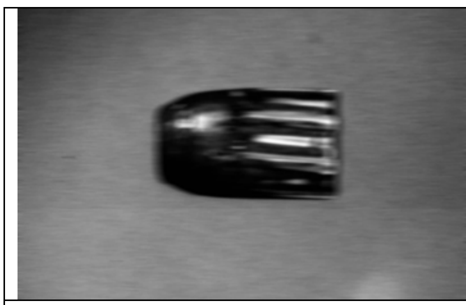
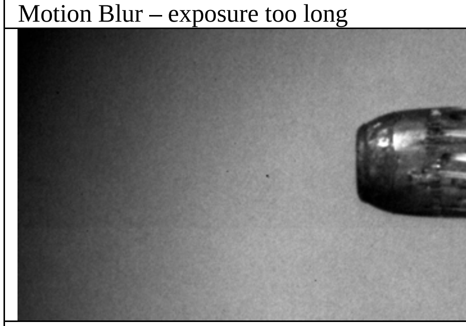
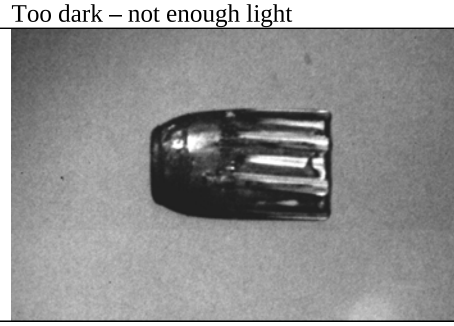
Ever since the invention of photographic materials, film makers, engineers and scientists have sought to understand the behaviour of objects which move faster than the eye can see. This presentation is an attempt to unveil some of the sometimes weird and wonderful methods and apparatus applied to this fascinating field over the years.

High speed imaging is almost as much an art as it is a science – we all know how very easy it is to take blurred snapshots as people look away from the camera or move out of the field of view. How many photo albums are full of disappointing images taken just after Junior scored his first goal for the team or grandma blew out those hundred candles just a moment ago!! Don't forget that magnificent view over the beach that got washed out by the bright sunlight or that hilarious picture of Uncle George falling over at the wedding, that you missed because the flash didn't go off (or wasn't switched on!).

These hurdles that we all have to overcome to get the perfect photograph are the bugbear of photographers, but they are the natural enemies of high-speed imaging

	
Motion Blur – exposure too long	Too dark – not enough light
	
Missed! – wrong timing	Just right

The Images of a .45 caliber handgun bullet above show these enemies in their true colours :-

Motion blur – the faster it moves, the shorter the exposure must be to get a clean image.

Lighting – get it wrong and see nothing – but don't forget that the shorter the exposure, then the brighter the light has to be.

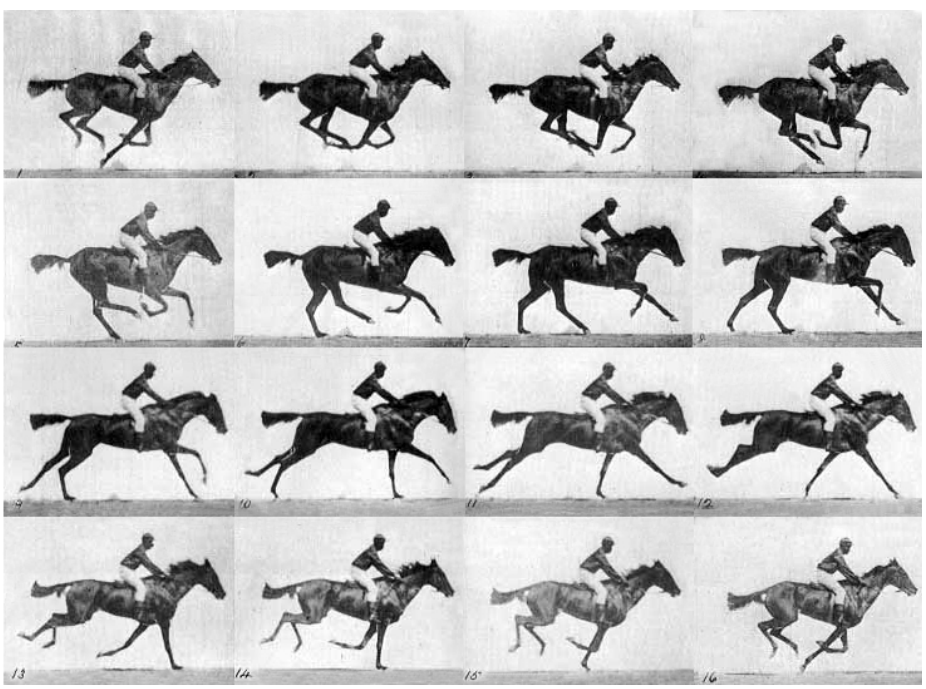
Timing – always a problem with action shots, but the faster the subject moves, the more precise the timing has to be to get the subject framed just right. You could always use a bigger field of view to capture a moving subject, but then detail and definition is lost and often the image is wasted.

One of the first practical applications of High Speed Photography was an investigation in 1873 by Eadweard Muybridge. Muybridge was a well respected photographer in his time, but before the advent of true motion film, the only way to represent motion was by taking successive still images of a subject and displaying them side by side or in quick succession.

When California governor Leland Stanford got into an argument in 1872 over whether all four feet of a horse are off the ground while it is galloping, he set the stage for the use of photographic instrumentation to settle the dispute.

Muybridge's first attempts using ordinary still photography proved futile.

Muybridge’s eventual solution was to set up an array of 24 separate cameras along a track (with a white background because he found that the contrast was better that way) and to expose each camera as the horse went by. He managed to synchronise his cameras with trip threads attached to the shutters which broke as the horse went by, thereby triggering each camera in turn. The results speak for themselves and clearly showed that all four of a horse’s hooves did leave the ground simultaneously!



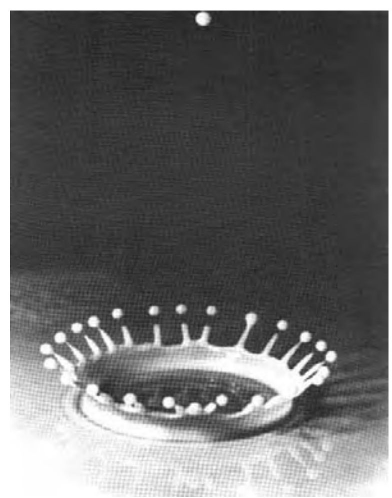
Sequence of a race horse galloping. Photos taken by Eadweard Muybridge (died 1904), first published in 1887 at Philadelphia.

It is worth pointing out that up until this time, all pictures used for the purposes of motion recreation were drawings or photographic-type transparencies of posed motion

High speed photography is not limited to motion pictures, as can be seen from this picture of a cannonball in flight taken by Thomas Skaife in 1853 at Woolwich Arsenal with a homemade early camera.

Mechanical shutters, although fine for stationary subjects or posed photographs, are simply not fast enough for most moving objects. This problem was largely overcome in the 1930's by Harold Edgerton, who is generally credited with pioneering the use of the stroboscope to freeze fast motion. He was professor of Electrical Engineering at MIT and developed the electronic flash which used inert gas to enhance the brightness of an electrical spark.

The famous milk drop picture by Harold Edgerton

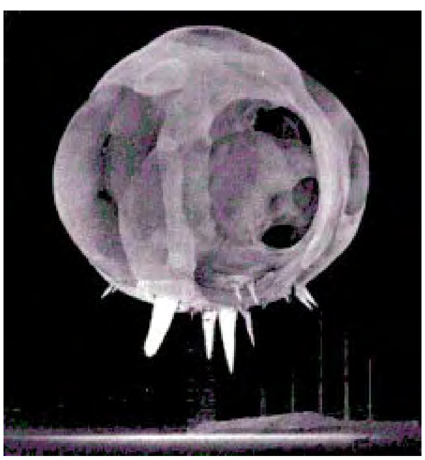


A water droplet rebounding, captured with a fast flash.

‘Doc’ Edgerton went on to found EG&G, which during the war years produced the Rapatronic camera.

The Rapatronic Camera – used a Kerr cell shutter which relies on two polarisers at 90 degrees to each other which normally block the transmission of light. A tube of nitrobenzene is placed between the two polarisers, and when a high voltage is applied across the nitrobenzene, this changes the polarisation of the light passing through it to then allow the light to pass through the second polariser.

These cameras were used during the Manhattan project to study the early stages of nuclear explosions and were often used in groups to capture the growth of the fireball, since each camera could only record a single image.



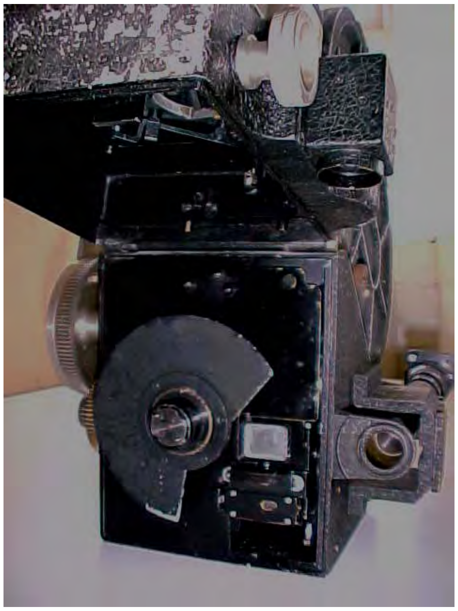
Nuclear explosion photographed with the Rapatronic camera less than 1 millisecond after detonation. The fireball is about 20 meters in diameter. The spikes at the bottom of the fireball are due to what is known as the rope trick effect. The rope trick effect is due to wires, used to stabilise the tower upon which the device was mounted, absorbing the energy from the initial flash of the explosion and vapourising almost instantaneously.

With the development of flexible celluloid film bases, real-time moving pictures became a reality. Early movie cameras at the beginning of the 20th century were sometimes over-cranked to allow motion to be slowed down, or even under-cranked to speed it up (on replay) to achieve artistic effects.

One camera designed especially for high speed cinema work, (an example of which is in the Specialised Imaging collection), is the Debrie HV model F from 1928. This camera used a rotating shutter and a patented indexing system which stopped the film in the gate to ensure the film didn't move while the shutter was open.

The camera carried a warning plate to advise operators not to run the camera at its maximum speed of 240 pictures per second for more than three seconds! Feedback to the operator was via two dials on the back of the camera showing speed and amount of film remaining

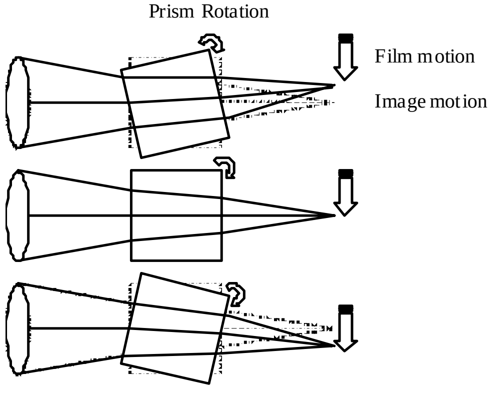
The long eyepiece at the side allowed focussing, with the lens being adjusted by the long lever at the top – a distance readout for setting the lens was obtained from a metal strip – this could be rotated to show different scales for each lens.



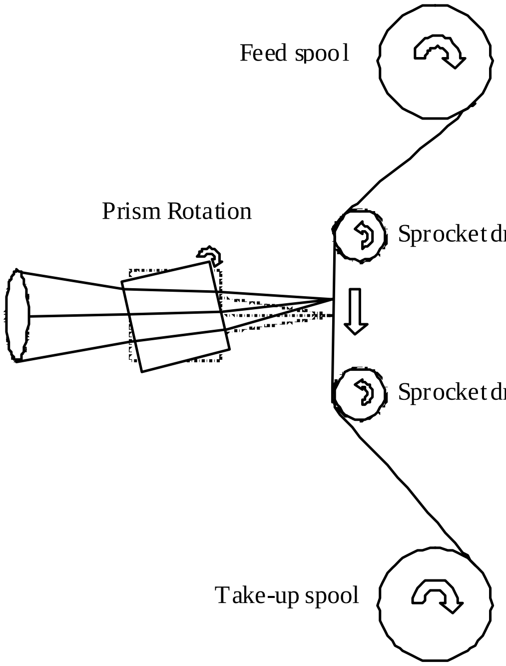
Front view of the Debrie camera with front latched back to allow the shutter plate to be changed to set a different exposure. The speed of rotation of the shutter is synchronised to the film speed, while the size of the gap in the disc sets the actual exposure time.

Rotating prism Cameras

All of the early film cameras were “intermittent motion” cameras. i.e. the film motion must be stopped during the exposure of each frame. When the framing rate of the intermittent motion camera is not high enough, camera designers compromised somewhat with the sharpness of the records obtained and designed cameras in which the film is in constant motion during the filming process. Since the film never comes to a standstill, a segmenting device is needed, and in the early 1930’s, F J Tuttle designed the rotating prism mechanism. This utilises the properties of refraction in the prism to effectively move the image as the prism rotates.



Representation of the effect of a rotating prism located between objective lens and film.



Basic arrangement of a rotating prism camera

Using this technique, much higher frame rates were possible

Eastman Kodak developed a high speed 16mm film camera using a rotating prism to achieve speeds of up to 250 frames per second driven by an electric motor. Bell telephone laboratories, one of the first customers for the Kodak cameras, used the system to study contact bounce in relays. This model was soon followed by the Eastman2 at 2500 frames per second, and the EK model 3 at 3000 frames per second.

The EK Model 3 shown here was manufactured in the early 1950's had an improved speed control

A very simple film path was all that was needed because the prism moved the image at the same speed as the film. Notice the lens at the bottom of the film transport. This relayed the image of a spark-gap onto the side of the film to record timing marks to allow later analysis of the results.

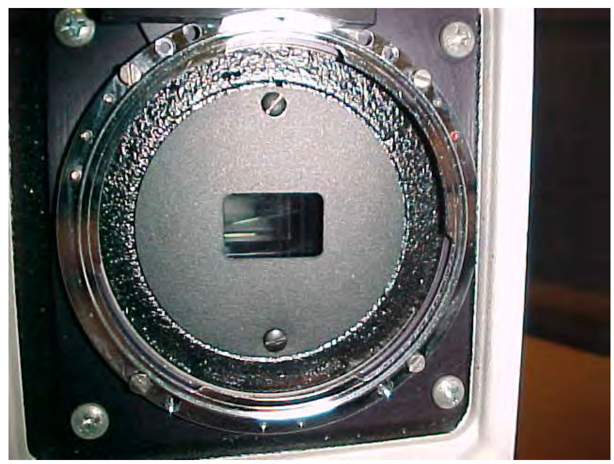
Close-up of the prism in the EK model 3 high speed film camera.

Note the prism mount obscures light transmission around the corners thereby effectively shuttering the system and avoiding defocusing of images as the prism rotates.

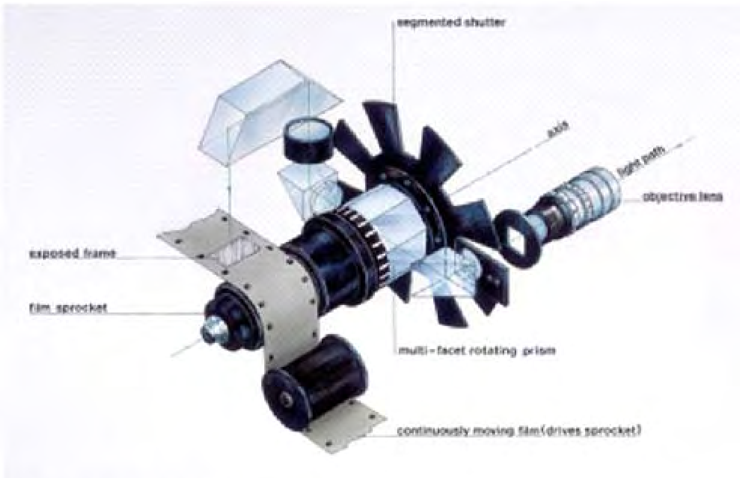
Bell labs later developed their own rotating prism camera (The Fastax) which was capable of 5000 frames per second

In the 1960's, other companies produced rotating prism cameras, including Redlake (Hycam), Photosonics, and John Hadland

Photec – 10,000 fps full height and up to 40,000 with ¼ frame prism conversion.

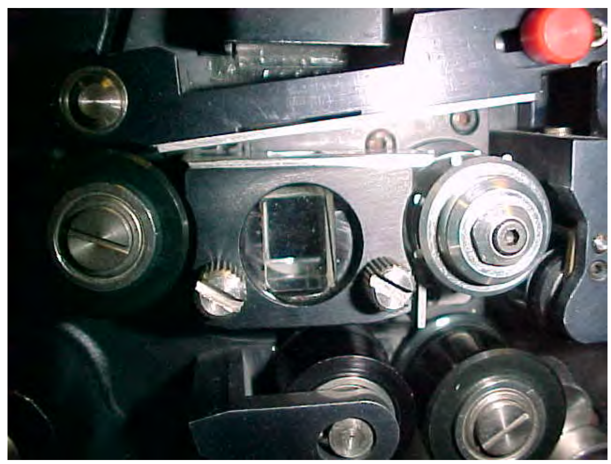


The Hadland Hyspeed was capable of 10000 frames per second full-height, 40000 ¼ height



OPTICAL PATH FOR HADLAND HYSPEED CAMERA

When even higher framing rates are desired these cameras can be equipped with prisms containing a larger number of facets and this allows doubling or quadrupling the full frame capability of the camera by respectively reducing the height of the individual frames to 1/2 or 1/4 their full frame dimension.

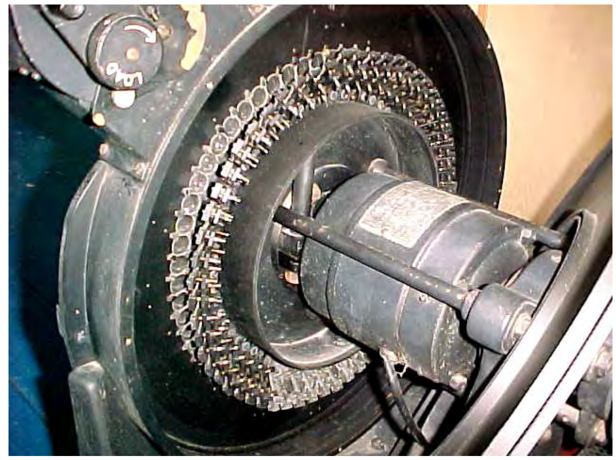


The Marley camera

A monster of a camera developed in 1944, this is actually an array of tiny separate cameras arranged in a circle with a rotating slit plate to expose each camera in turn (actually a number of slits in the rotating plate, but the principle remains the same).

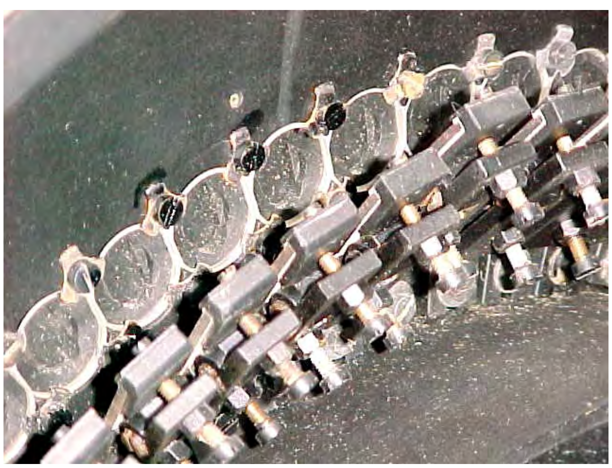
In the Marley camera, the film remained stationary, and images were formed on the film by the individual camera lenses

16 slots in the rotating shutter disc and 63 individual camera lenslets and mirrors allow the camera to expose all 63 images onto film positioned around the inside of the drum in 1/16th of a rotation.



The system is basically a phased array of cameras, each with a slightly different viewpoint, but imaging at long distances makes this limitation rather insignificant.

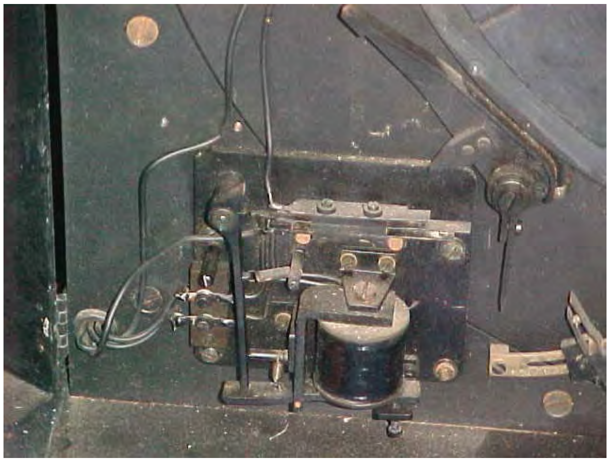
A set of matching hole plates on a second disc located between the slit plate and lenses acts as a triggered capping shutter



cose-up view of the individual lenses and mirrors – each one had to be individually adjusted to get the images into focus on the film!

A close-up view of the trigger mechanism – the solenoid at the bottom releases a spring-loaded lever which actuates the capping shutter. At the other end of the lever is a bar which operates a set of contacts which may then be used to trigger the event the camera is looking at .

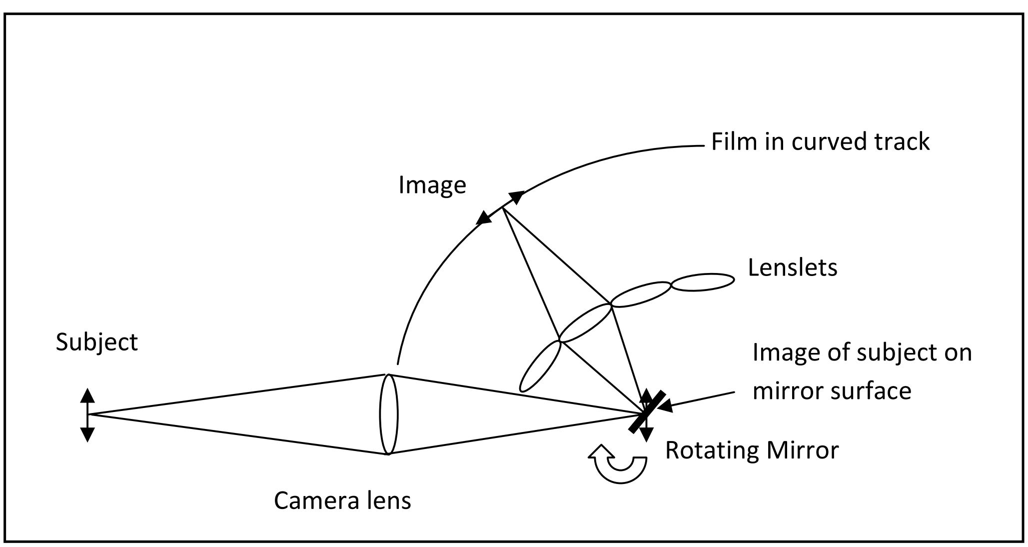
Some of the slit apertures in the main rotating disc can be seen here



The trigger mechanism shown post-firing

Rotating mirror cameras

When even higher framing rates than are possible when moving film, a compromise is then typically made in terms of the total number of images acquired. For photography at rates of millions per second, the film is actually held still and the image of the subject can be moved to successive positions by means of a rotating mirror. The primary image collected by the camera's objective is brought to a focus and is then re-imaged on the surface of a rotating mirror. This mirror is surrounded by an array of lenslets which in turn re-image the subject's image formed in the mirror onto film which is held in an arc at the appropriate distance from each lenslet.
An image is only formed by each lenslet when the mirror is in the right orientation, thus for rotational speeds of thousands times per second, millions of frames per second can be recorded, albeit for only a very short time, or number of frames. To get the maximum speeds, turbines are often used to drive the mirror rather than electric motors



Schematic of a rotating mirror framing camera

Significant problems in triggering are associated with this type of camera and capping shutters are needed both before and after the event. Framing rates are maximised when the lenslets are small, therefore resulting in smaller images. Rotating mirror cameras are still made today, and even variants with multiple CCD's in place of film.

Video

High speed video systems started to evolve very soon after CCD video cameras. In the early days, memory was too expensive a medium for recording the large amounts of data needed for meaningful recordings. Most of the early high speed camera systems used modified video tape recorders to record individual fields of video – giving frame rates of 50 or 60 frames per second. Exotic synchronous rotating shutters were used to minimise motion blur.

The Kodak company Spin Physics was one of the first companies to bring out a custom system which ran at 1000 frames for 2 seconds utilising a custom sensor with multi-channel readout (512 x 384 pixels.

This is the NAC HSV1000 which used a CMOS sensor to reach 1000 frames per second in 1990.

The system had a custom modified VHS recorder built into the trolley which allowed easy deployment, particularly in industrial environments.

Here's a much later Kodak Ektapro HS model 4540

This system uses a 256 x 256 sensor and gives 4500 frames per second or up to 40,500 partial frames

Digital storage helps to keep the size down and greatly increases the performance by allowing instant replay of recorded sequences through a standard PC.

A multi-channel readout custom CMOS sensor allow the latest Phantom V12.1 to produce 1280 x 800 resolution at 6242 frames/second, 67000 at 256 x 256, and an optional 1,000,000 frames/second at 128 x 8

On board memory of up to 32GB and gigabit Ethernet make a very compact and easy to deploy system.

One of the latest developments, using a custom, patented, CCD sensor with 100 frames of storage on-chip is the Shimadzu HPV-1 camera. This system, although having limited sensor resolution of 312 x 260 pixels, is capable of maintaining full resolution at rates up to 1 million frames per second.

Images from a 10,000 frames per second video sequence of a concrete sample test. Courtesy Shimadzu corporation, Japan.

Streak and Strip Cameras

A significant number of specialised applications employ cameras in which the film is in motion at the time of exposure. In their simplest manifestation film is simply moved past a stationary slit and the exposure itself takes place during the transit of the film across this opening.

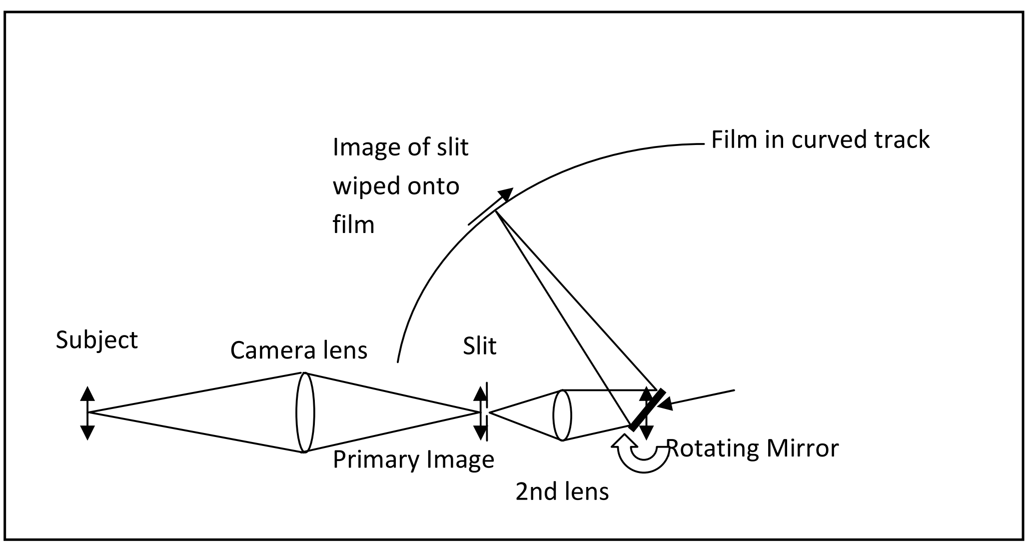
Unlike normal cameras that make photographs that have two spatial dimensions, these “strip” or “streak” cameras always display time as one of their dimensions and one subject spatial dimension as their other dimension.

The classic example of this type of camera is the race finish camera where the film is set into motion as the race leaders approach the winning post – as the horses pass the slit, an image is formed which can be used to compare very precisely which runner arrived at the post (slit) first. The faster t he film moves, the more accurate the relative timing will be.

Cameras that employ this scheme for making photographs but whose output resembles the subjects they are photographing depend on moving the film at the same rate as the subject moves past the stationary slit.

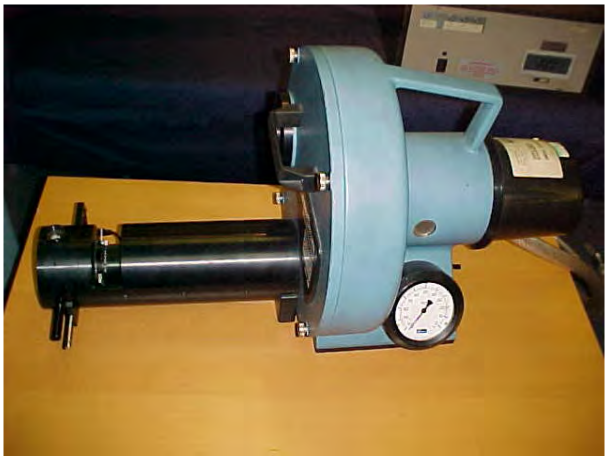
Synchroballistic photography – just like the race finish application is where an image of a subject (in this case a projectile) is created by moving the film past the slit in synchronism with the passing projectile. Clearly if the speed of the film is wrong, then the image will be distorted, but if the speed is correct, then as the subject passes the slit, an image is formed of the subject with each part being recorded at a slightly different time. Synchroballistic photography overcomes the problem of accurate triggering normally associate with ballistic events

A streak camera is simply an extension of this idea, but moving the film even faster. To get the maximum speed out of a streak film camera, engineers applied the same techniques as framing cameras. For example, if the lenslets are removed from a rotating mirror camera, and a slit placed in the optical path, we have a very fast streak camera



Schematic of a rotating mirror streak camera

Another interesting manifestation of film streak cameras is the Drum camera. A limitation of the rotating mirror design is that the length of film which can be used is limited by the useful angle of the mirror as it rotates. To overcome this, the drum camera was conceived. This consists of a fixed set of optics imaging the slit onto the inside of a large drum which is then lined with film and spun at a fast rate.



Shown here is a Cordin Drum Streak Camera.

The streak optics at the front contain an interchangeable slit with relay optics to transfer the image into the drum where a mirror turns the image to focus onto the film

With the front removed, the rotating drum is shown. This is driven by a powerful motor to achieve the speed necessary for fast recording.

The steering mirror is visible at the bottom of the front cover.

Often this type of camera was used with laser illumination to overcome the shuttering problems which have to be addressed to avoid overwriting the required image on the film. These cameras were very large and difficult to use but did produce excellent results.

Electrostatic streak cameras

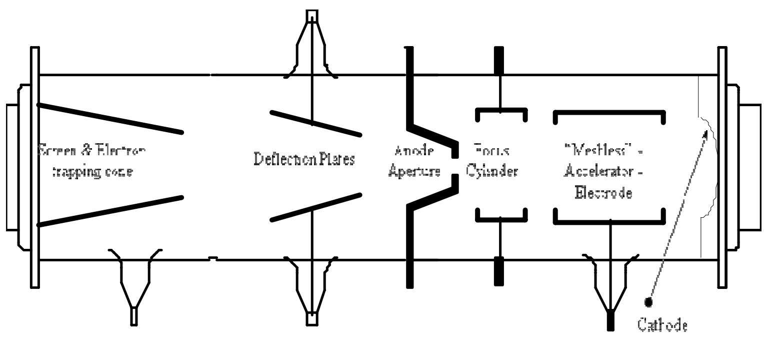
Streak cameras are invaluable for very fast events where there is insufficient time to acquire a series of two-dimensional images using a framing camera. e.g. explosive events where the progress of a detonation front can be easily analysed against time in a single axis. Or where the object of the study is to analyse how intensity varies with time. e.g laser pulse shape or telecoms LED drivers.

However, many of the events that needed to be studied were getting faster and faster, and even with rotating drum and mirror solutions, results were poor.

Because the limitation with film-based systems was having to mechanically move either the image or the film, the best solution was to move the image electrically – not possible with light, but once the light is converted to electrons, then this becomes easier. Thus the streak (or image converter tube was born.

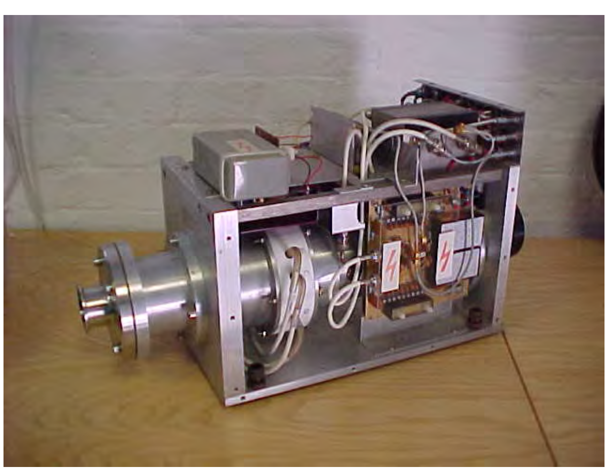
Typical streak tube

This type of device consists of a light sensitive photocathode which generates electrons directly from the incident light, then a focusing and accelerating system to guide the electron beam through deflection plates (rather like an oscilloscope tube), before being focused onto s phosphor screen where the electrons are converted back into light.



Schematic layout of typical streak tube.

As can be seen from the schematic, this is a fairly simple structure in principle. In practice, very complex high voltage circuitry is needed to drive such tube to achieve linear streak deflections at extremely fast rates. Cameras were produced by various companies, notably Hamamatsu and Hadland from the 1960's onwards. Speeds capable of resolving just a few picoseconds were developed. Readout of results was generally through Polaroid film, but more recently CCD detectors have been used.



This type of sreak camera is still in manufacture today, using the same basic principles, and sub picoseconds resolution is now achievable.

Image Converter Framing cameras.

The idea of deflecting electrons to generate time resolved images was also applied to framing cameras – using the standard Image Converter tubes, but with a rectangular mask instead of a slit, meant that two-dimensional images could be generated on the phosphor screen, and by simply adding a second set of detector plates, two or more rows of images could be obtained. This method was used to generate framing sequences at rates up to 600 million.

One of the main disadvantages of this type of camera was that to change imaging speed meant changing the tube drive circuitry – this circuitry had to be matched to a particular tube and consisted of finely tuned circuits – typically a multi-speed camera system would have a range of plug-in modules to achieve a desired speed range.

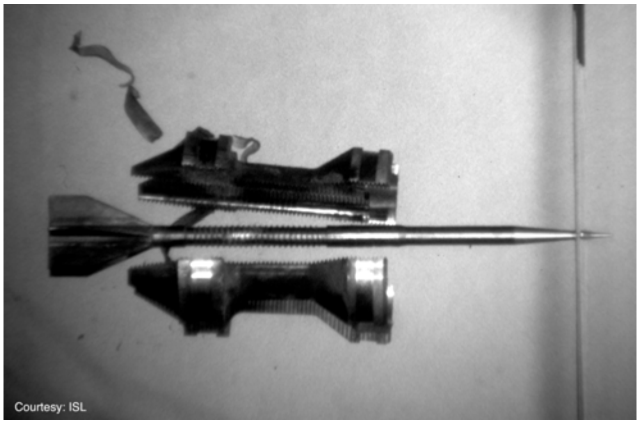
A Hadland 790 is shown here. This camera was capable of both streak and framing operation and was the work horse of many research establishments. Many of these cameras are still in regular use today.

Developments in image converter framing cameras continued until the early 1990s, with almost all readouts becoming CCD based as imaging technology developed. Film is extremely sensitive, and can respond well to even very low light output levels. However in some framing cameras and almost all streak cameras the light levels were getting so low that additional light gain had to be introduced, and therefore stages of image intensification were introduced between the Image Converter and the readout. It was the addition of these image intensifiers which allowed the less sensitive CCD detectors to be used in conjunction with phosphor outputs.

CCD's

Early CCD's were originally designed as replacements for the old fashioned Tube based TV cameras, and as such were only designed with a relatively slow readout method which while perfect for TV work, did no favours for people wanting short exposures to stop fast motion. Because image intensifiers had been introduced at the output of image converters, the next logical step was to couple an image intensifier to a CCD to allow the intensifier to be used as a fast shutter and also to allow some photonic gain.

This development led to products such as the ballistic Range camera from Hadlands – designed around a CCD camera developed by Polaroid, Hadland added a fast gated image intensifier and a rugged environmental housing and took the ballistics market by storm. Now users could acquire images of projectiles almost instantly with 1134 by 488 pixel resolution

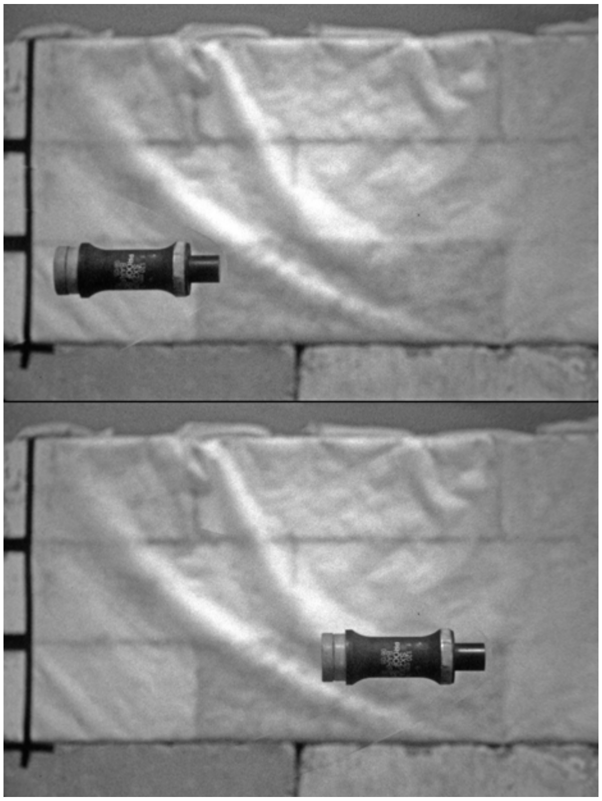


A typical single-shot ballistic range camera image showing Sabot separation from a 40mm APFSDS round

Pictures show the Hadland SVR2 ballistic range camera

Progress has continued to be made on these ballistics cameras. The latest offering from Specialised Imaging is the SIR2 camera, equipped with a 40mm high resolution image intensifier and Kodak CCD with 4000 by 3000 pixel resolution – added to this the camera can take two images in quick succession to allow even better analysis of results from a single round.

The Specialised Imaging SIRII ballistic range camera. 4000 by 3000 pixels, 20ns exposure.



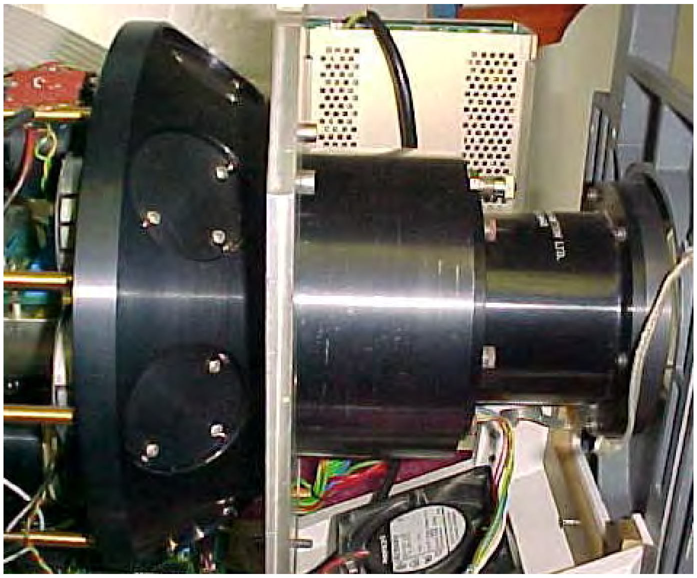
Typical result from the SIRII camera – this image pair taken in available light (no flash lamps) of a 120mm projectile travelling at approximately 1500m/s with 500ns exposures

Image courtesy QinetiQ, Shoeburyness

In the early 1990's, this CCD and intensifier technology was finally applied to the framing camera with the launch of the Hadland Imacon468

The Hadland Imacon468 camera

The breakthrough that made possible a CCD framing camera was an innovative pupil-split optical system

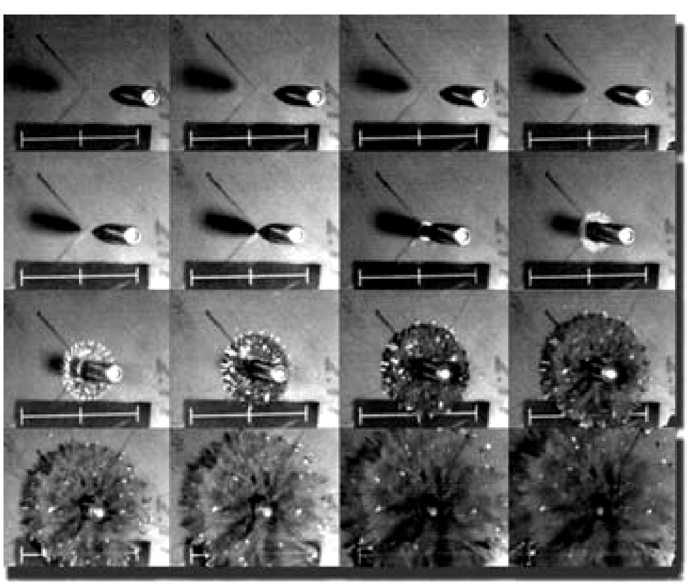


Imacon 468 optical beamsplitter – used a pyramid mirror to divide the incoming light into eight separate paths. Individual CCD's with coupled 18mm image intensifiers provided up to 8 imaging channels with 576.

As high-speed framing cameras grew into the digital age, the benefits of full programmability of timing, exposure, and intensifier gain allowed more flexibility in a framing camera than ever before possible. Even though these cameras only had a maximum of eight exposures, the fact that these exposures could be positioned anywhere in time with 10 ns accuracy meant that even the most complex imaging problems could be solved. The 18mm channel plate image intensifiers meant that even though the input light was divided eight ways, there was sufficient gain to achieve good exposures even at 10ns exposures.

Additional benefits of the programmability of these cameras are that the exposure may be changed on a frame-by frame basis as may the individual intensifier gain. Using both of these parameters together, events exhibiting dynamic range changes in excess of 10,000:1 over the duration of the event can be recorded with properly exposed images throughout!

Further improvements were made to this system as electronics evolved, resulting in the Hadland Imacon 200 camera in 2000. This version used a fast decay phosphor for the image intensifiers allowing two images to be taken a few hundred nanoseconds apart – thereby giving a maximum of 16 images albeit at the expense of sensitivity and ultimate resolution. New interline CCDs were also employed as part of the upgrade giving 1280 x 1024 pixel images.



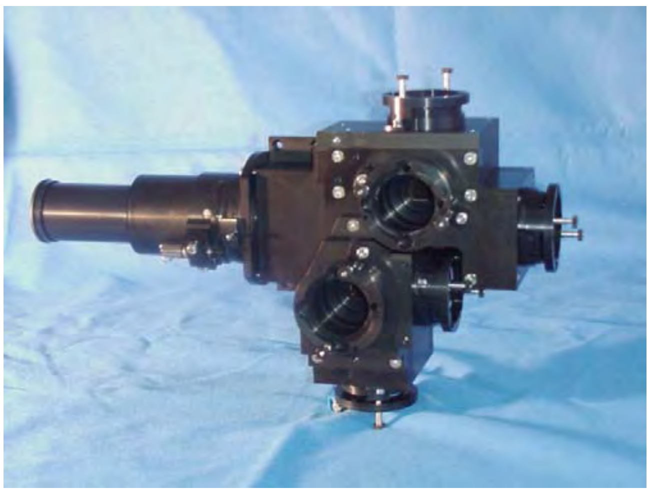
Imacon200 brochure image

This system, although producing excellent results does suffer from a few limitations.

Optically, the pupil split wasn't the best idea, as this leads to a number of defects including shading, parallax and astigmatism.

The use of the faster phosphor introduces image lag problems at short separations and also reduces the resolution of the intensifiers.

To overcome these problems, Specialised Imaging designed the SIM series of ultra-high-speed framing cameras



SIM beamsplitter.

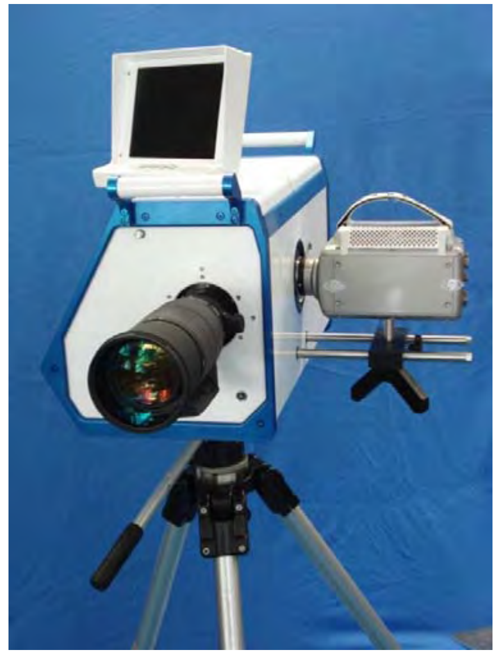
This design uses non-polarising prisms as the splitting element which completely eliminates all of the issues associated with a mirror-pupil split. Parallax and astigmatism are completely removed.

The beamsplitter looks "odd" because of the way the optical paths have been folded to minimise the footprint, but this design allows up to 16 separate optical channels to be used. This means that cameras can be made with 16 CCD's and produce artefact free images with much higher resolution (the system is capable of 50 lp/mm).

The Specialised Imaging SIM camera

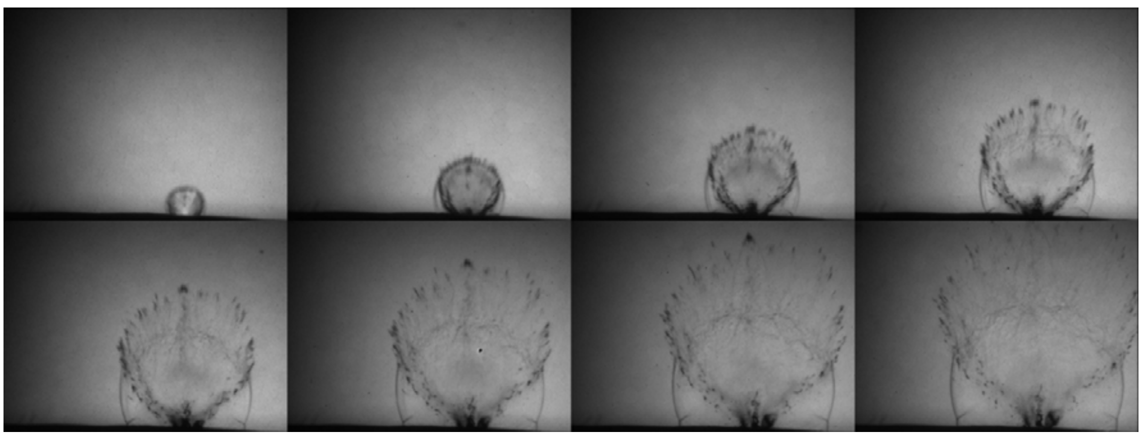
An innovation in the optical design of this camera is the unique auxiliary optical port. This allows an additional instrument such as a high-speed video, streak camera or time resolved spectrometer to be coupled to the framing camera, allowing even more information to be gathered about the event being studied

The SIM camera with a Vision Research Phantom 7 camera coupled to the auxiliary viewport

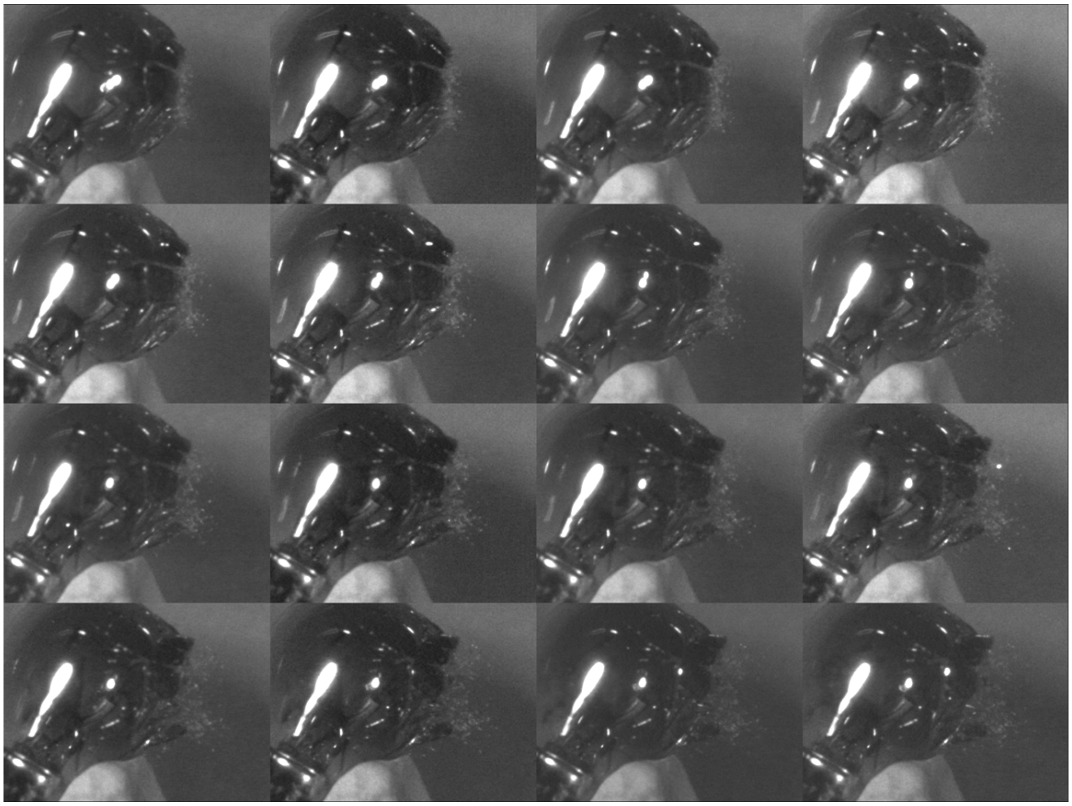


When used in this configuration, the high-speed video gives a long-duration view of the overall event, and the SIM framing camera can be used to reveal the fine temporal and spatial detail of critical parts of the subject behaviour

Image sequence of a slapper-plate blast initiator

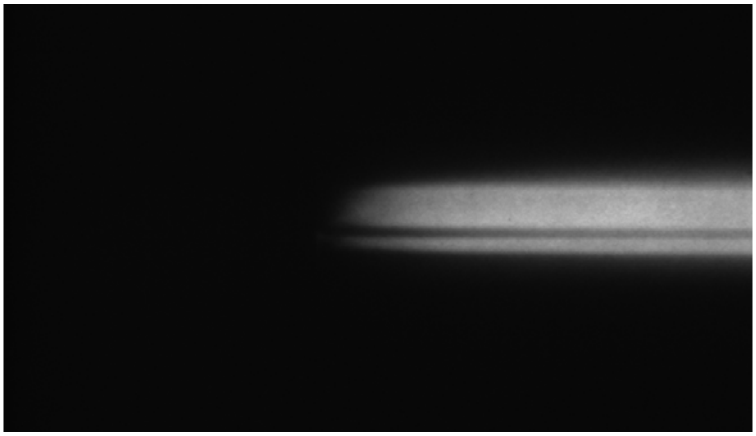


courtesy of e2V technologies, Lincoln showing supersonic ejecta and shockwaves

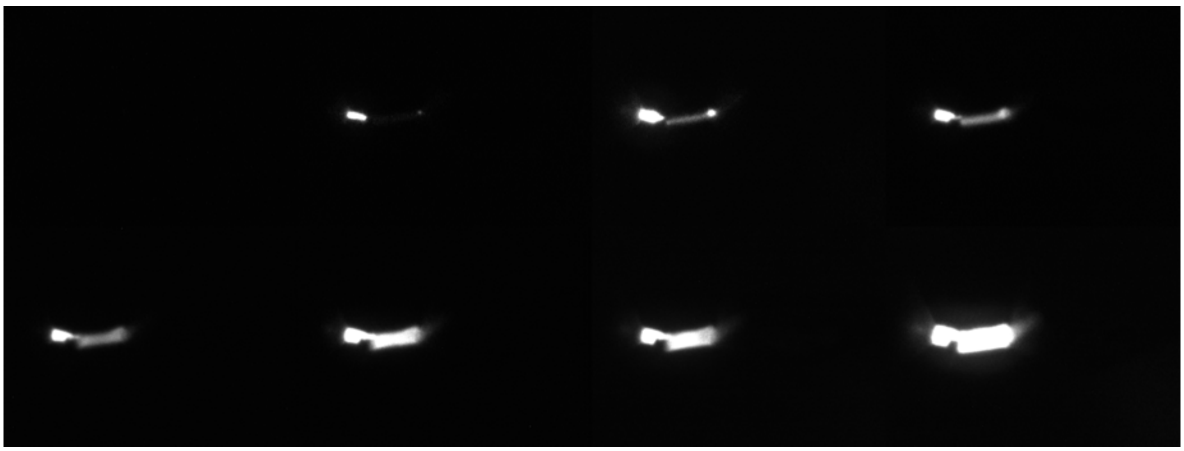


16-frame sequence of pellet impacting a small bulb

The SIM series of cameras can be optically coupled to any manufacturer's streak camera. Shown here coupled with an Optronis Streak camera



Streak record showing turn on of spark gap. Total time window 2 microseconds with 100 um slit.



Triggered spark gap at 50 Mfps with 10ns exposures. Total time Window recorded 220 nanoseconds.

Typical streak and framing sequence

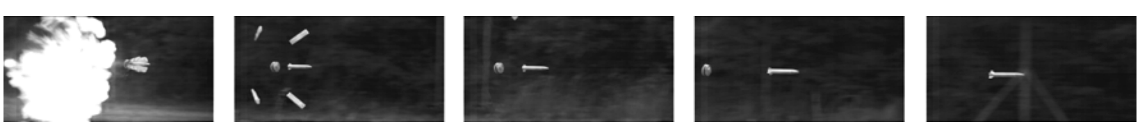
Projectile Follower systems

In order to fully evaluate failure modes of projectiles, it is often necessary to observe the performance of a round over a significant portion of its trajectory. To achieve this with a number of single shot cameras would be prohibitively expensive.

A concept pioneered by UK and USA defence research establishments consists of a computer controlled rotating mirror in front of a high-speed Video camera. The mirror is programmed to rotate at the correct speed such that the camera will "follow" the projectile as it passes thereby removing motion blur from projectile – so longer exposures are possible to get better quality images

Disadvantages – small mirror low sensitivity unwieldy system repeatability/accuracy?

The SIT has, been developed to provide consistent and accurate tracking of projectiles in flight using a scanning mirror and high-speed video camera. This equipment allows observations to be made of the behaviour of projectiles in flight for over a hundred metres. The SIT system consists of a rugged mirror and control unit housing, a 3-axis mount, and laptop computer.



- Ballistics
- Detonics
- Plasma
- Impact studies
- Combustion research
- Low light machine vision system
- Elasticity, crack propagation and shock resistance
- Medical testing and research
- Spray and particle analysis
- Nanotechnology and micro-machines

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