Study of rotational and translational motion of objects using high speed imaging techniques augmented by MATLAB.

Internship Report

By

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Last but not least, we would like to thank every person who was involved directly or indirectly in making this project successful.

PREFACE

A famous saying, "The theory without practical is lame and practical without theory is blind.

My Institute has come forward with the opportunity to bridge the gap between theoretical knowledge and practical knowledge by allowing me to learn something at DRDO as a summer internship program. The report documents the work done during the summer internship at the Imaging wing, Proof and Experimental Establishment (PXE), DRDO, under the supervision of Sri Tanmoy Mohanty, Scientist-D. The report first shall give an overview of the task completed during the internship period with technical details. Then the results obtained shall be discussed and analyzed.

This report is based on the study of imaging techniques using high speed cameras in PXE and its application in the measurement of ballistic parameters. The first part of this report provides insight into high speed imaging techniques, including the various concepts of camera systems, its various components like lens, shutter, aperture, sensors, etc. It displays a brief idea of High Speed Imaging.

In short, this report is a power-packed package that enables the readers to have a basic idea of high speed imaging and a small demonstration of rpm and acceleration measurement of rotational and translational systems respectively using high speed cameras aided by software named ‘Photron Fast Cam Viewer’ in scientific applications.

CONTENTS

DRDO

DRDO is the R&D wing of the ministry of defence, Govt. of India with a mission to provide India with cutting edge technologies and an aim to achieve self-reliance in defence technologies and systems, simultaneously equipping our armed forces with state of the art weapon systems. DRDO was established in 1958 after the merger of Technical Development Establishments (TDE) & the Directorate of Technical Development & Production (DTDP).

DRDO has a network of 52 laboratories which are deeply engaged in developing defence technologies covering various disciplines, like aeronautics, armaments, electronics, combat vehicles, engineering systems, instrumentation, missiles, advanced computing and simulation, special materials, naval systems, life sciences, training, information systems, agriculture, radars, electronic warfare systems etc.

India domestically produces only 45% to 50% of defence products it uses, and the rest are imported. To become technology research and production leader, reduce reliance on the imports and increase self-reliance, DRDO Chief called for more collaboration with the industry, private sector, research and educationinstitutesincluding IITs and NITs. India's military–industrial complex has had little success and only recently private sector was allowed to enter the defence production.

As part of Make in India and Atmanirbhar Bharat initiative, DRDO under Development cum Production Partner programme (DCPP) allowed handholding of domestic private sector industries to improve their development and production cycle of complex defence systems.

PXE

Proof & experimental establishment (PXE) located on the coast of Bay of Bengal at Chandpur, Odisha, at a distance of 15 km from Balasore city, is the oldest establishment of DRDO. In March 1894, the first proof testing in India was carried out, with there being fired six inch (152 mm) Bag Loader Howitzers and 12 Pounder Shrapnel shells under the command of Captain R.H. Mahon. He recommended the creation of a dedicated department for this purpose. The proof department in India was sanctioned in May 1895. It was established on 7 November 1895, with headquarters at Balasore. The establishment started functioning sometime in 1896 with Capt. RT Moore, R.A., as the first Proof Officer. Since its establishment, it has seen an exponential growth especially after independence when it was brought under the administration of DRDO in 1958.

The proof and experimental establishment (PXE) is responsible for design and developmental trials of guns, mortars, rockets, RCL, tank guns and their ammunition, including naval guns and ammunition. PXE also conducts performance evaluation trials for tank armor and ammunition, as well as proof of armor plates, tank turrets, ICVs, proximity fuzes. Today PXE is internationally acclaimed proof range with state of the art facilities.

At present, the establishment has a notified range of 50 km in length along the sea coast and 50 km into the sea. The range is a natural sea based range with oscillating tide conditions. During low tide, water recedes to a distance of about 3 km into the sea beach, thus facilitating various range operations. It also conducts technical evaluation trials for weapons and ammunition.

PROJECT DESCRIPTON

Title – To study the rotational and translational motion of objects using high speed imaging techniques augmented by MATLAB.

Hardware used – Photron Fast Cam with Nikon 35mm lens.

Software used – Photron FastCam viewer (PFV) and MATLAB.

- For rotational motion – 2 Quads were used on alternate blades of a fan. The coordinates of the centre of the quads were tracked using the PFV software which were then used to build an algorithm on MATLAB to calculate the RPM of the fan.

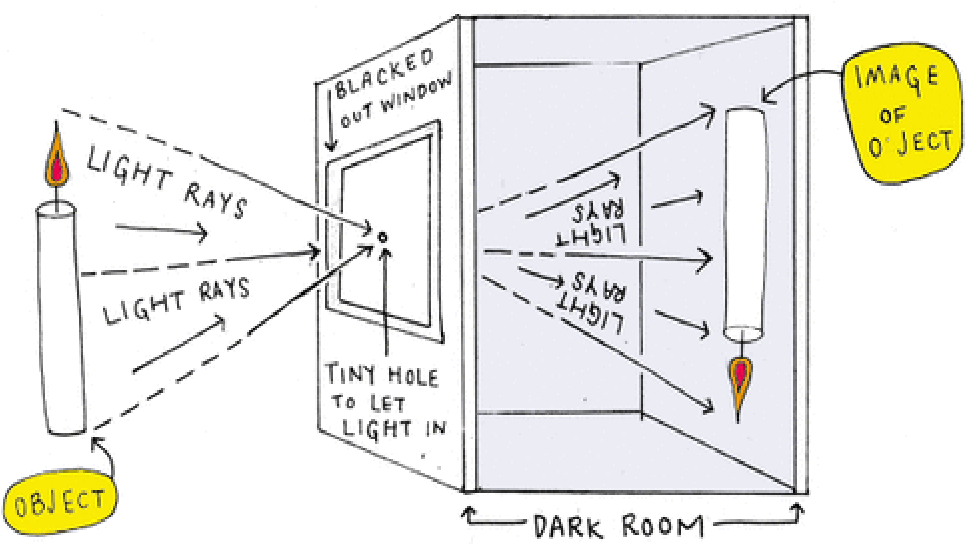
- For translational motion – A Quad was pasted on an objected which was subjected to free fall. The coordinates of the centre of the quad was tracked using PFV software, which was then used in a MATLAB algorithm to calculate the acceleration of the object, which ideally should come out to be g ($9.81\ m/s^2$).

BRIEF HISTORY OF CAMERA

1. **Camera Obscura: Alhazen** is said to have actually invented the camera obscura, as well as the pinhole camera which is based on the same idea. He carried out experiments with candles and described how the image is formed by rays of light traveling in straight lines.

Camera obscura is a device in the shape of a box or a room that lets the light through a small opening on one side and projects it on the other. In this simple variant, an image that is outside of the box is projected upside-down. More complex cameras can use mirrors to project image upwards and right-side up and they can also have lenses. Camera obscura is used as an aid for drawing and entertainment.

Camera obscura is a very old device. Oldest mention of its effect is by Mozi, Chinese philosopher and the founder of Mohism, during the 5th century BC. He noticed that an image from camera obscura is flipped upside down and from left to right as a result of light moving in a straight line. The Greek philosopher Aristotle noticed in the 4th century that light from a sun eclipse that passes through holes between the leaves, projects an image of an eclipsed sun on the ground. Passing of light in the straight line also noticed Euclid 4th century BC and Theon of Alexandria in 4th century AD.



Camera obscura can also refer to analogous constructions such as a box or tent in which an exterior image is projected inside. Camera obscuras with a lens in the opening have been used since the second half of the 16th century and become popular as aids for drawing and painting. The concept was developed further into the photographic camera in the first half of the 19th century, when camera obscuras boxes were used to expose light-sensitive materials to the projected image.

The camera obscura was used to study eclipses without the risk of damaging the eyes by looking directly into the sun. As a drawing aid, it allowed tracing the projected image to produce a highly accurate representation, and was especially appreciated as an easy way to achieve proper graphical perspective.

2. **Glass/metal-plate type: Photographic plates** preceded photographic film as a capture medium in photography, and were still used in some communities up until the late 20th century. The light-sensitive emulsion of silver salts was coated on a glass plate, typically thinner than common window glass.
Glass plates were far superior to film for research-quality imaging because they were stable and less likely to bend or distort, especially in large-format frames for wide-field imaging. Early plates used the wet collodion process. The wet plate process was replaced late in the 19th century by gelatine dry plates.

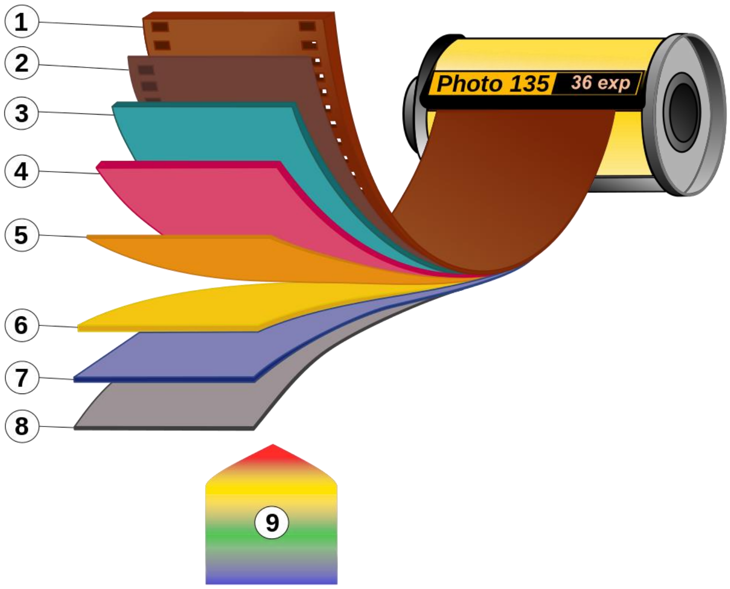
Glass plates were far superior to film for research-quality imaging because they were stable and less likely to bend or distort, especially in large -format frames for wide-field imaging. Early plates used the wet collodion process. The wet plate process was replaced late in the 19th century by gelatin dry plates.

Glass plate photographic material largely faded from the consumer market in the early years of the 20th century, as more convenient and less fragile films were increasingly adopted. However, photographic plates were reportedly still being used by one photography business in London until the 1970s , and by one in Bradford called the Belle Vue Studio that closed in 1975. They were in wide use by the professional astronomical community as late as the 1990s. Workshops on the use of glass plate photography as an alternative medium or for artistic use are still being conducted.

3. **Photographic film type:** Photographic film is a strip or sheet of transparent film base coated on one side with a gelatine emulsion containing microscopically small light-sensitive silver halide crystals. The sizes and other characteristics of the crystals determine the sensitivity, contrast, and resolution of the film.

The first flexible photographic roll film was sold by George Eastman in 1885, but this original "film" was actually a coating on a paper base. As part of the processing, the image-bearing layer was stripped from the paper and attached to a sheet of hardened clear gelatine. The first transparent plastic roll film followed in 1889. It was made from highly flammable cellulose nitrate film.

Although cellulose acetate or "safety film" had been introduced by Kodak in 1908, at first it found only a few special applications as an alternative to the hazardous nitrate film, which had the advantages of being considerably tougher, slightly more transparent, and cheaper. The changeover was completed for X-ray films in 1933, but although safety film was always used for 16 mm and 8 mm home movies, nitrate film remained standard for theatrical 35 mm films until it was finally discontinued in 1951.



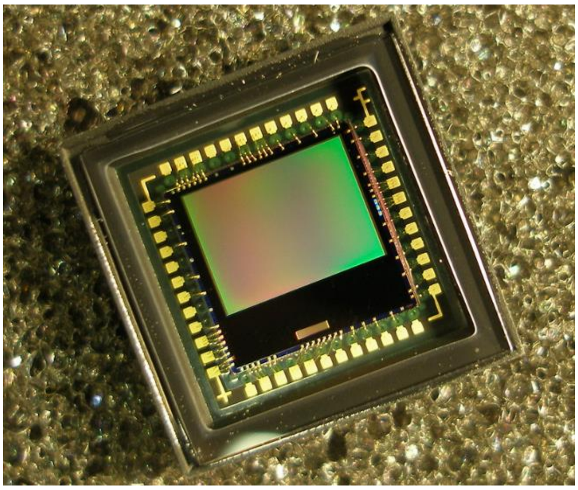
Layers of 35 mm color film:

1. Film base
2. Subbing layer
3. Red light sensitive layer
4. Green light sensitive layer
5. Yellow filter
6. Blue light sensitive layer
7. UV Filter
8. Protective layer
9. Visible light exposing film

4. **Solid state image sensor type:** Early analog sensors for visible light were video camera tubes. They date back to the 1930s, and several types were developed up until the 1980s. By the early 1990s, they had been replaced by modern solid-state CCD image sensors.

The basis for modern solid-state image sensors is MOS technology, which originates from the invention of the MOSFET by Mohamed M. Atalla and Dawon Kahng at Bell Labs in 1959. Later research on MOS technology led to the development of solid-state semiconductor image sensors, including the charge-coupled device (CCD) and later the active-pixel sensor (CMOS sensor).

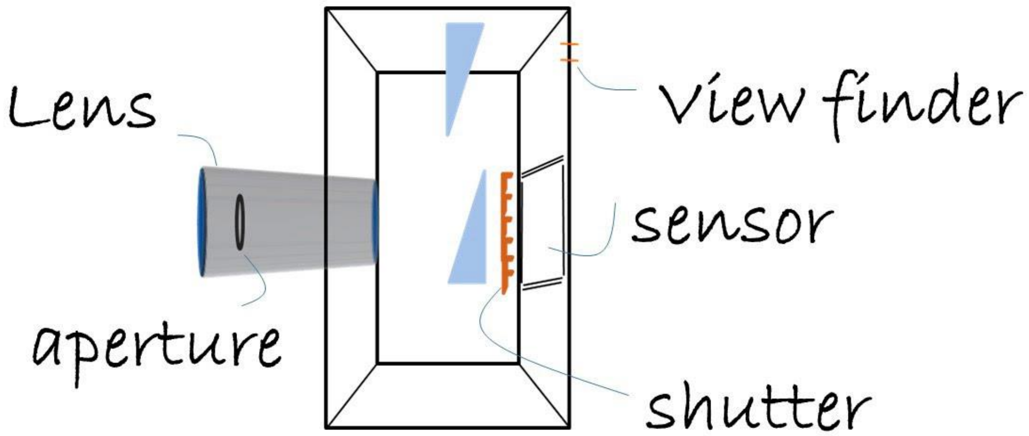
The charge-coupled device (CCD) was invented by Willard S. Boyle and George E. Smith at Bell Labs in 1969. While researching MOS technology, they realized that an electric charge was the analogy of the magnetic bubble and that it could be stored on a tiny MOS capacitor. As it was fairly straightforward to fabricate a series of MOS capacitors in a row, they connected a suitable voltage to them so that the charge could be stepped along from one to the next. The CCD is a semiconductor circuit that was later used in the first digital video cameras for television broadcasting.



Early CCD sensors suffered from shutter lag. This was largely resolved with the invention of the pinned photodiode (PPD). It was invented by Nobukazu Teranishi, Hiromitsu Shiraki and Yasuo Ishihara at NEC in 1980. It was a photodetector structure with low lag, low noise, high quantum efficiency and low dark current. In 1987, the PPD began to be incorporated into most CCD devices, becoming a fixture in consumer electronic video cameras and then digital still cameras. Since then, the PPD has been used in nearly all CCD sensors and then CMOS sensors.

In the early 1990s, American companies began developing practical MOS active pixel sensors. In 1991, Texas Instruments developed the bulk CMD (BCMD) sensor, which was fabricated at the company's Japanese branch and had a vertical APS structure similar to the Olympus CMD sensor, but was more complex and used PMOS rather than NMOS transistors.

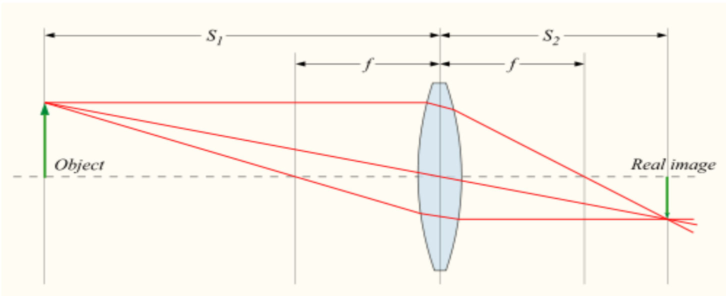
How Does A Camera Work?

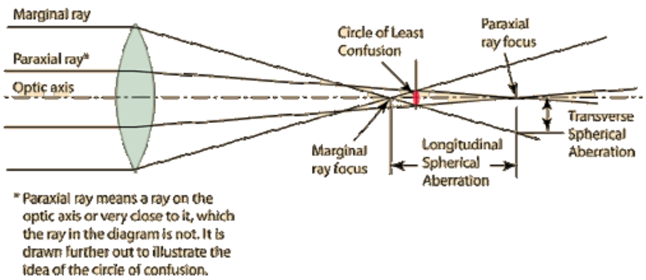


Basic Components:

1. Lens system
2. Aperture
3. Shutter
4. Sensor

LENS SYSTEM





Basic Lens categories:

1. Prime lenses
2. Zoom lenses

Types of lenses used in Photography:

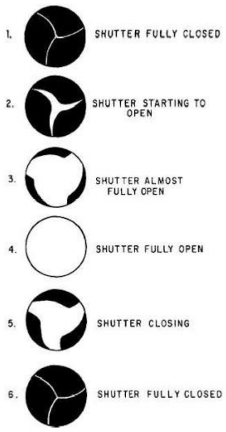
1. Macro lenses
2. Telephoto lenses
3. Wide angle lenses
4. Specialty lenses

SHUTTER

Shutter is a device/ mechanism that determines the duration during which the sensor is exposed to external light. There are two broad classes of shutter - One is a mechanical shutter and the other is an electronic shutter.

Advantages of electronic shutter over mechanical shutter:

1. Silent operation
2. Faster frame rate
3. Reduced shake/blur



(Electronic Shutter)

(Mechanical shutter)

HIGH SPEED IMAGING

High-speed imaging is the science of taking pictures of very fast Phenomena. In 1948, the Society of Motion Picture and Television Engineers (SMPTE) defined high-speed imaging as any set of photographs captured by a camera capable of 128 frames per second or greater , and of at least three consecutive frames. High -speed imaging can be considered to be the opposite of time-lapse imaging. In common usage, high-speed imaging may refer to either or both of the following meanings.

The first is that the photograph itself may be taken in a way as to appear to freeze the motion, especially to reduce motion blur. The second is that a series of photographs may be taken at a high sampling frequency or frame rate. The first requires a sensor with good sensitivity and either a very good shuttering system or a very fast strobe light.

The second requires some means of capturing successive frames, either with a mechanical device or by moving data off electronic sensors very quickly. Other considerations for high-speed photographers are record length, reciprocity breakdown and spatial resolution.

The use of high speed cameras to capture digital high speed video isn't about capturing an amazing image, it's about improving human knowledge of the inner workings of the world. High speed cameras have the capacity to record the details of rapid mechanical movements and replay them in slow motion. From applications where high light sensitivity is required to those in which high g-force and vibration are present, digital high speed video slows down countless processes to a speed that allows for greater study in government applications , military development etc.

PROCESS OF HIGH SPEED IMAGING

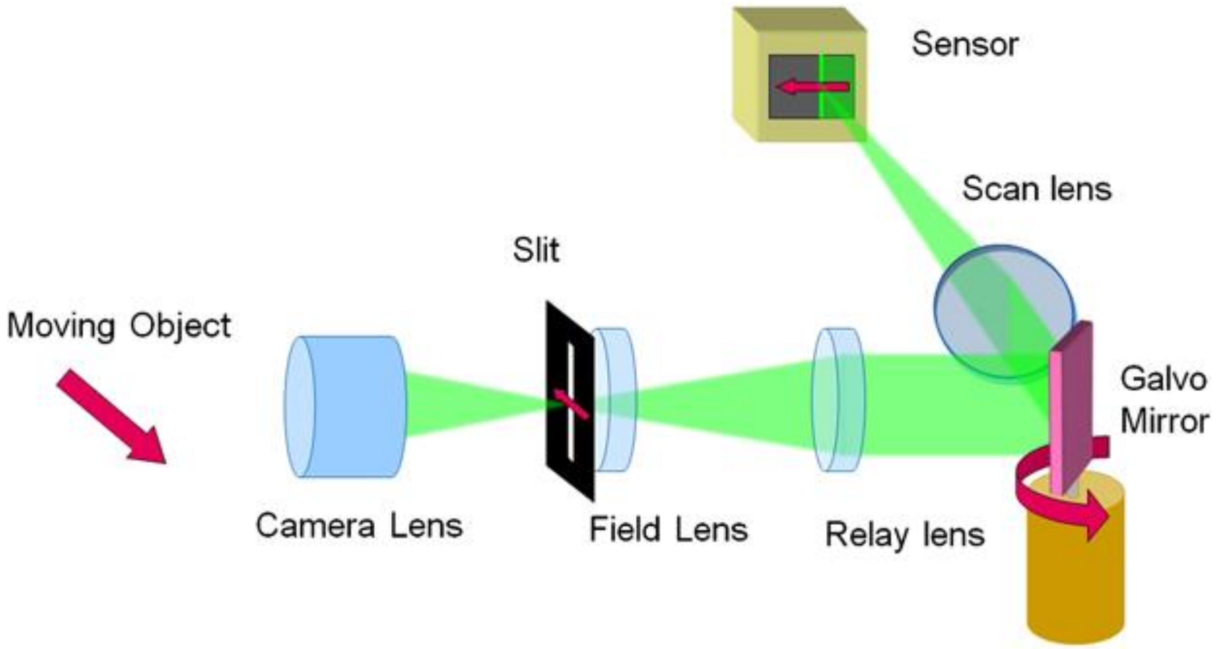
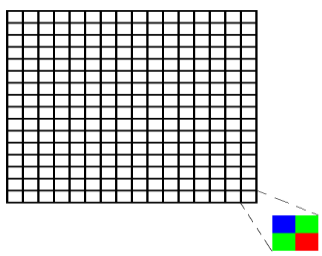


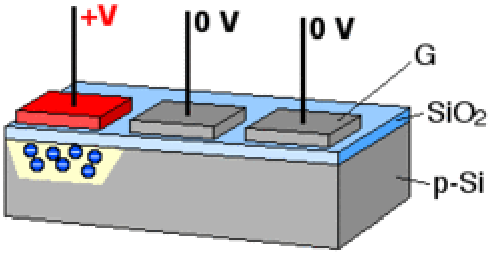
IMAGE SENSORS

Image sensor: Two dimensional (2D) array of picture elements called pixels . Spatial discretization by pixels.



Pixel: Pixel is defined as a minute area of illumination on a display screen, one of many from which an image is composed. In digital imaging, a pixel, pel, or picture element is the smallest addressable element in an all points addressable display device;

so it is the smallest controllable element of a picture represented on the screen.



Characteristics parameters of Image sensors:-

1. Responsivity
2. Noise Equivalent Power
3. Quantum efficiency
4. Response time
5. Linearity
6. Spectral response

TYPES OF IMAGE SENSORS:-

1. Photoconductor(LDR)
2. Photodiode
3. Phototransistor
4. CCD
5. CMOS

- **Photoconductor:-**

  1. It is basically a resistor.
  2. Resistance is inversely proportional to Light Intensity.
  3. Slow response time.

- **Photodiode:-**

  The Photodiode is reverse biased silicon diode in which the electron hole pairs are produced near depletion region or exposure to the light. If the incident light has the greater energy than the silicon's energy band gap (Eg)

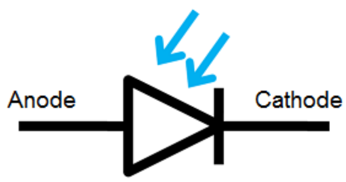
, the electrons and holes along the concentration gradient in the PN junction. When they are accelerated by an external electric field, electrons and holes are diffused into N and P layers respectively. As a result, if both the edges of the PN junction are open, an **emf (**Voc) is produced across the PN junction and a current (Ip) flows through the junction in reverse direction if a load is connected across it. More is the light, more is the reverse current .In this type of photo detector, dark current will be quite low as it is reverse current caused by the thermally produced minority carriers. Total current is the dark current plus current due to light.

Materials commonly used to produce photodiodes are **silicon, Germanium and Indium Gallium Arsenide & Lead Sulphide.** Because of their greater band gap , **Silicon** based photodiodes generate less noise than **Germanium** - based photodiodes but **Germanium** photodiodes must be used for wavelengths longer than approximately 1µm.

Photodiode is a type of photo detector capable of converting light into either current or voltage, depending upon the mode of operation.

Principle of operation:

A photodiode is a PN junction or PIN structure. When a photon of sufficient energy strikes the diode, it excites an electron thereby creating a mobile electron and a positively charged electron hole pair. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in field of the depletion region. Thus holes move towards the anode, and electrons toward the cathode, and a photocurrent is produced.



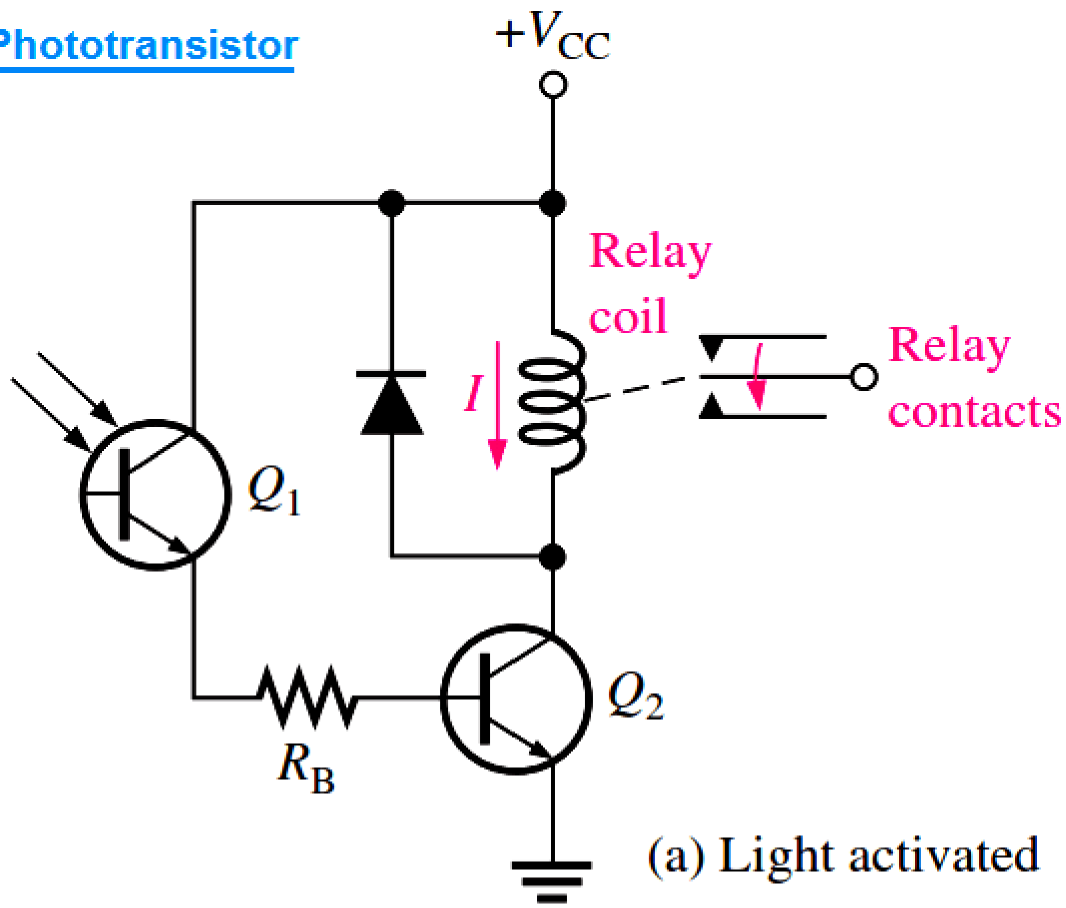
Photodiode symbol

- **Photo Transistor :-**

It has a larger P-type base area to obtain a large collector current with base-collector junction. The phototransistor consists of the equivalent of a photodiode using base-collector junction and NPN transistor, which amplifies the photocurrent output of the diode.
When a phototransistor is exposed to light with positive & negative voltages applied to its respective collector & emitter, the reversely biased photodiode (composed of the base-collector junction) produces a photocurrent, which serves as the base current for the following transistor. The transistor provides an output current which is an h_{fe} multiple of the photocurrent:
$I_c = I_p(1 + h_{fe}) = h_{fe} * I_P$

I_P: photocurrent of the photodiode
h_{fe}: common emitter amplification factor of this transistor

Phototransistor



- **Charged coupled device (CCD) :-**

The **CCDs (Charged-coupled device)** are sensors based on an array of passive photodiodes which integrate charge during the exposure time of the camera. The charge is then transferred to common electronics which reads the accumulated charges of the different pixels and translates them in voltages.

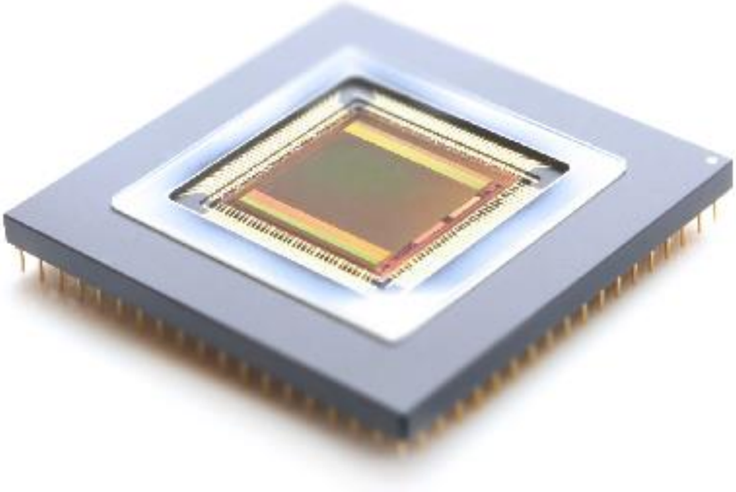
The CCD is a passive-pixel device, the quantum efficiency is very high which an advantage in applications is where the light is quite poor. Furthermore, since the electronics are the same for all the pixels (or, at least, for the pixels of the same column), a high pixel uniformity is achieved.

Also the charge transfer is quite slow resulting in a low frame rate (<20fps) which is a disadvantage. A CCD sensor is a charged coupled device. It is a silicon chip with several photosensitive spots. Because it is an analog device, the output is converted to a digital signal at once by an analog-to-digital converter.

Working Principle of CCD:

The charges can be shifted along the row and finally taken out. This is equivalent to line scan in electron tube based cameras. By taking the output from each row in sequence, a field scan can also be achieved and thereby we can generate a video output signal that represents light intensity variation falling on a CCD array.

The photon-induced electrons must be collected, via an electric field within the silicon, into a localized region near the front surface of the chip. The end pixel is transferred in a special pixel array called the serial register. Each movement of charge resulting from gate potential changes is called a clock cycle, in which the serial register receives many clock cycles for each cycle of the full pixel array. The net result is a sequence of charge packets emerging from the serial register, each of which is directly proportional to the amount of light striking a particular location on CCD.



Charges in that row are transferred out of the sensor using the charges coupling technique, making room for the next row to be shifted out, and the next, and so on. In the case of digital cameras, before being transferred out of the CCD serially, each pixel charge is amplified resulting in an analog output signal of varying voltage. This signal is sent to a separate chip called analog to digital converter (ADC) and there resultant digital data is converted into bytes that comprise the raw representation of the image as captured by the sensor prior to any post processing. After an exposure, charges on the first row are transferred to a read out register then passed to an amplifier, and on to an analog to digital converter. The charge on each row coupled to those on the row above. So after the row that is read moves into the register, the next row moves down to take its place.

Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create ‘charge packets’. Each packet corresponds to one pixel.

- **CMOS(MOSFET):**

The **CMOS (Complementary metal-oxide semiconductor)** are sensors based on an array of active pixel: the pixel-level electronics (typically 3 or 4 transistors) translates the charge accumulated in the photodiode in a well-defined voltage; in this way, the output of each pixel needs only to be acquired and sampled.

Since the pixel output relies on voltage (rather than on charge), with CMOS sensors it's possible to achieve higher frame rates due to the easier readout scheme and it makes it possible to define the region of interest that is to be acquired.

This readout scheme has the disadvantage of exploiting a higher noise as there are readout transistors in each pixel and as a result there is a non-homogeneity in the image due to the mismatches across the different pixel circuitries.

CMOS sensors are increasingly becoming the favoured option of machine vision camera manufacturers as they are economical and rising proficiency. A CMOS sensor is a digital device. Charges from a photosensitive pixel are converted to a voltage at the pixel site using a CMOS sensor. The signal is then multiplexed to numerous on-chip digital-to-analog converters by row and column. CMOS sensors have a fast response time, low sensitivity, and a lot of fixed-pattern noise.

Limiting its present utility is a very high voltage application. However when the high switching frequencies are parameters the power MOSFET often remains the device of choice. When the voltage requirement increases, does the ON resistance of the POWER MOSFET devices.

CCD vs CMOS:

1. **Mobile phones drive CMOS imager volume**

With the goal of lower power consumption and higher integration for smaller components, CMOS designers focused efforts on imagers for mobile phones, the highest volume image sensor application in the world. A huge amount of investment was made to develop and fine tune CMOS imagers and the fabrication processes that manufacture them. As a result of this investment, we observed great improvements in image quality, even as pixel sizes shrank.

Therefore, in the case of high volume consumer area and line scan imagers, based on almost every performance parameter imaginable, CMOS imagers perform better than CCDs.

2. **Imagers for Machine Vision**

The success in the field of machine vision, area and line scan imagers can be attributed to the enormous mobile phone imager investment to displace CCDs. For most machine vision area and line scan imagers, CCDs are also a technology of the past.

The performance advantage of CMOS imagers over CCDs for machine vision merits a brief explanation. For machine vision, the main parameters are speed and noise. CMOS and CCD imagers differ in the way that signals are converted from signal charge to an analog signal and finally to a digital signal. In CMOS area and line scan imagers, the front end of this data path is massively parallel. This allows each amplifier to have low bandwidth. By the time the signal reaches the data path bottleneck, which is normally the interface between the imager and the off-chip circuitry, CMOS data are firmly in the digital domain.

In contrast, high speed CCDs have a large number of parallel fast output channels, but not as massively parallel as high speed CMOS imagers. Hence, each CCD amplifier has higher bandwidth, which results in higher noise. Consequently, high speed CMOS imagers can be designed to have much lower noise than high speed CCDs.

However, there are important exceptions to this general statement. The major applications where CCD sensors outperform CMOS sensors are Near Infrared Imagers, Ultraviolet Imagers etc.

Further Comparisons:

<u>CCD</u>:

1) CCD sensors have been mentioned earlier to create high quality low noise images.

2) CCD on the other hand consumes as much time as an equivalent CMOS sensor.

3) CCD chips can be highly expensive. CCD sensors have been mass-produced for a large period of time so they are more mature.

4) CCD can be used in cameras that focus on high quality images with a lot of pixel & excellence light sensitivity.

<u>CMOS</u>:

1) CMOS sensors are traditionally more susceptible to noise because each pixel of a CMOS sensor has several transistors located next to it and the light sensitivity of a CMOS chip is lower.

2) CMOS sensors traditionally consume less power due to the use of sensors in CMOS.

3) CMOS chip can be fabricated on just about any standard silicon line so they tend to be expensive.

4) CMOS sensor has lower quality lower resolution & lower sensitivity CMOS camera is less expensive and has longer battery life.

Application of photo sensors:

•Camera

.Safety equipment

.Communication

.Industry

Application of photo sensors in PXE:

. As Flash detector

. CCD camera

• Fuze delay time measurement

. Time to burst measurement

•Measurements of hang fire time

KEY TERMINOLOGIES USED IN IMAGING

Pixel Resolution: No. of pixels in row (M) and column (N). Resolution: M × N.

Ex: 1024 × 1024 (1 MP).

Frame rate: No. of images/frames recorded per second expressed in fps.
High Speed camera- capable of exposure < 1ms and frame rate > 250 fps.

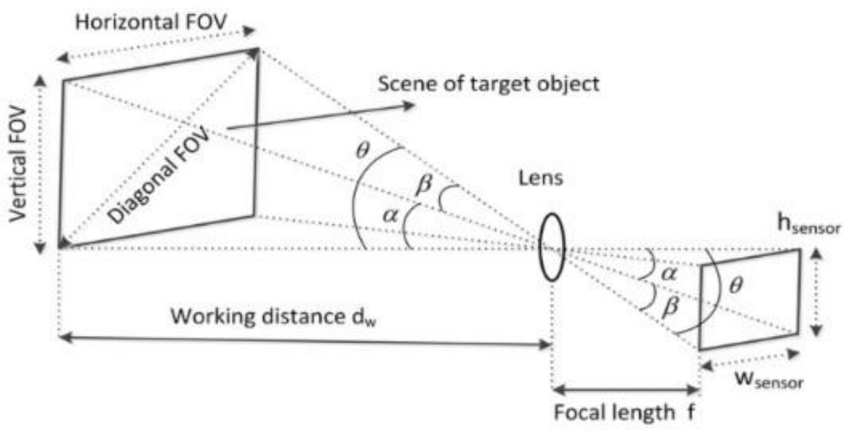
Exposure time: Time duration of exposing the sensor to the external light.

Important factor to remove motion blur and also proper illumination of sensor.

Focussing:
Adjusting the Distance between Lens system center and image sensor to obtain sharp Image.

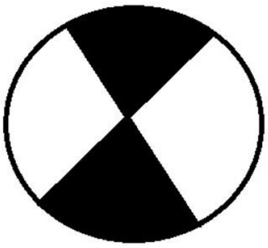
Trigger:
Recording a transient event.

Command to be sent to the on- board memory to Start/stop Recording.



ANALYSIS OF ROTATIONAL MOTION

Description: Quads were pasted on alternate blades of a fan. The coordinates of its centre were captured at different time intervals which was then used to determine the speed of rotation of the blades of the fan.



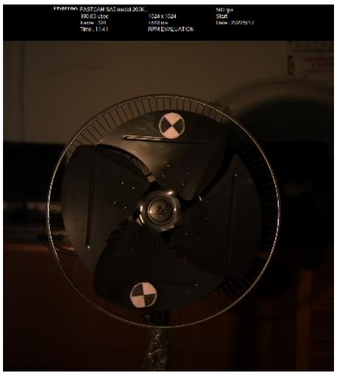
(Quad)

The rotations were captured using Photron FastCam viewer in 250 and 500 frames per secs, respectively. The coordinates of the centre of the quad was recorded frame by frame. The angle it traversed with respect to the centre of the fan was calculated and the value was used to calculate the speed of rotation by dividing it with the frames elapsed in terms of secs.

$$\omega = \frac{d\theta}{dt}$$

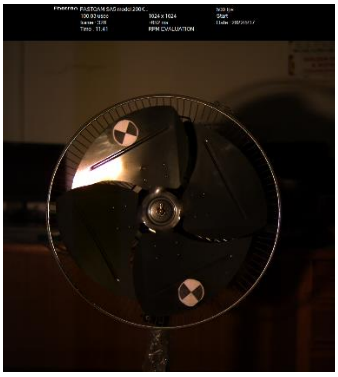
ω was calculated for the tabulated readings and the variation in ω was plotted using MATLAB.

Few captured frames for 500 fps in high mode are shown in the next page.



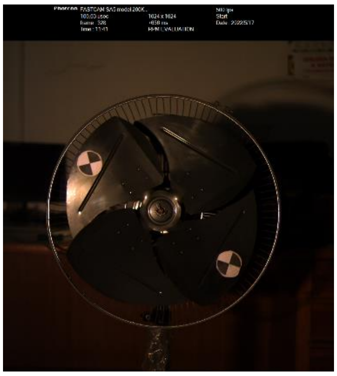
Frame count 324

Frame count 325



Frame count 326

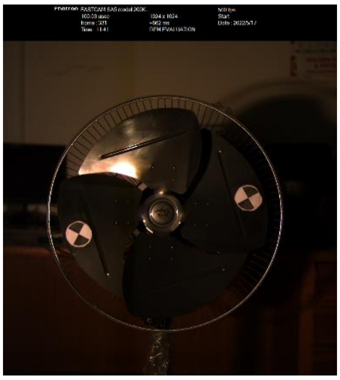
Frame count 327



Frame count 328

Frame count 329

Frame count 330



Frame count 331

Frame count 332

Frame count 333

Frame count 334

Frame count 335

TABULATION FOR HIGH MODE IN 500 FPS

Frame Count	X Coordinate	Y Coordinate
324	521	373
325	447	375
326	377	396
327	313	437
328	268	492
329	238	558
330	223	627
331	233	701
332	256	769
333	303	829
334	363	868
335	430	896

MATLAB CODES

- Fixing the coordinates of the constants parameters

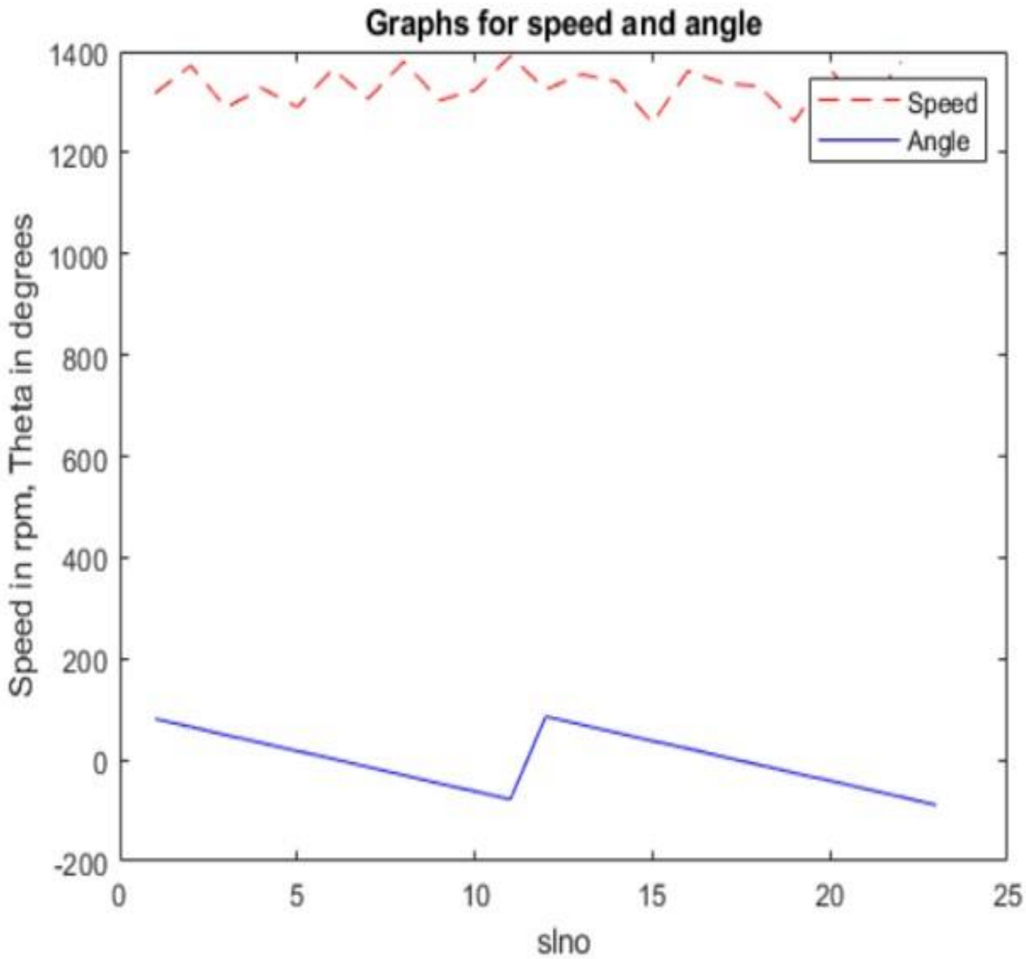
```
% Constants
C = [486 ;638];
fps = 500;
n=24;
p=2;
slno = [1:(n-2)];
% Initializing x-coordinate vector, y-coordinate vector, theta vector and omega vector
x = [447;377;313;268;238;223;233;256;303;363;430;504;576;644;697;734;753;751;730;689;632;566;490;418];
y = [375;396;437;492;558;627;701;769;829;868;896;902;888;855;802;742;668;593;521;463;412;383;373;381];
theta=zeros((n-1),1);
omega= zeros((n-2),1);
% Computation of theta vector
for i =1:(n-1)
    theta(i)=(180/pi)*(atan((y(i)-C(2))/(x(i)-C(1))));
    % disp(['The value of angle in degrees is : ', num2str(theta(i))])
end
```

- Computing ω

Computation of omega vector

```
for i = 1:(n-2)
    if (theta(i) > theta(i+1))
        omega(i)=abs((60/(2*pi))*(((pi/180)*(theta(i+1)-theta(i)))/(1/fps)));
    else
        omega(i)=p*(abs((60/(2*pi))*(((pi/180)*(theta(i+1)+theta(i)))/(1/fps))));
    end

    % disp(['The value of speed in rpm is : ',num2str(omega(i))]);
end
% Plot of omega vs slno and theta vs slno
plot(slno,omega,'--r');
xlabel('slno');
ylabel('Speed in rpm, Theta in degrees');
title('Graphs for speed and angle');
hold on
slno=[1:(n-1)];
plot(slno,theta,'-b');
legend('Speed','Angle');
shg
% Display results
%disp(theta)
%disp(omega)
% Calculation of average speed
avgSpeed = sum(omega)/(n-2);
```

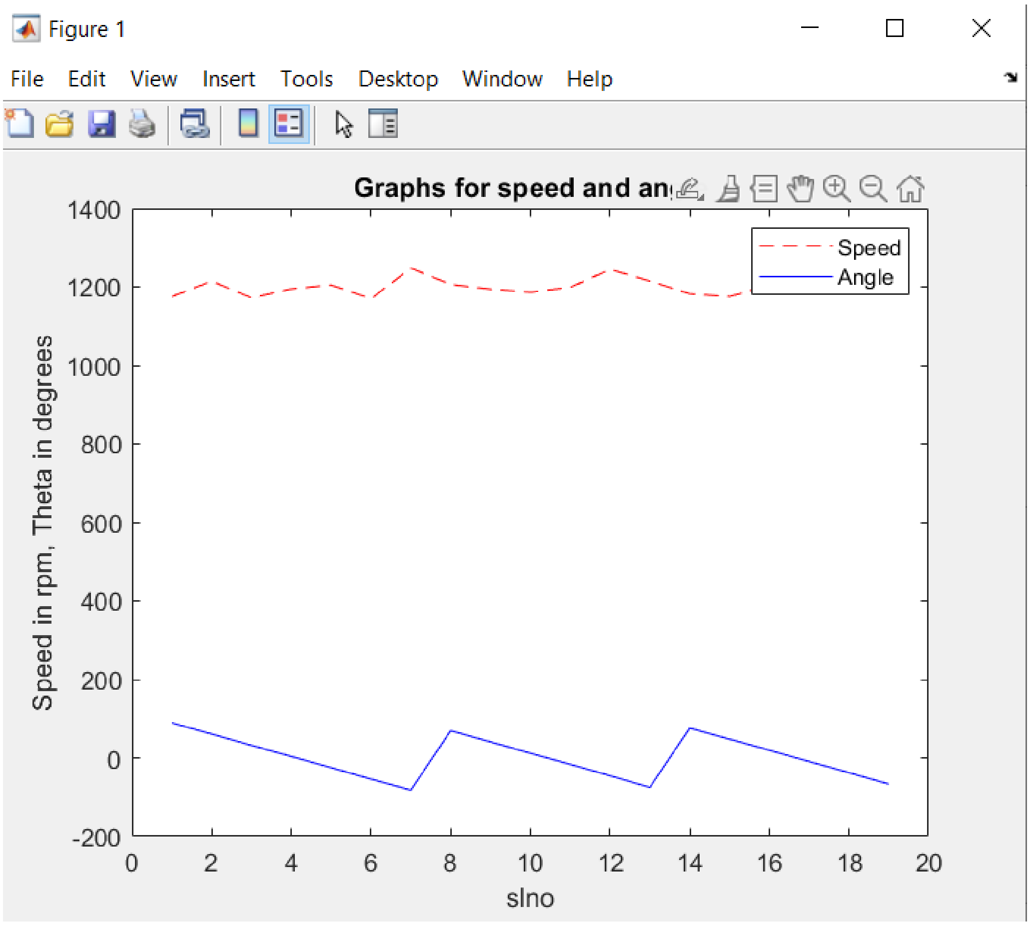
- Variation of ω obtained for different frame count



Similarly, 6 different graphs were obtained for low, med and high setting of the fan at 250 and 500 fps respectively.

- Low setting, 250 fps

Frame Count	X Coordinate	Y Coordinate
756	482	373
757	357	406
758	260	498
759	219	621
760	244	751
761	328	855
762	449	902
763	580	890
764	689	812
765	746	693
766	742	562
767	673	449



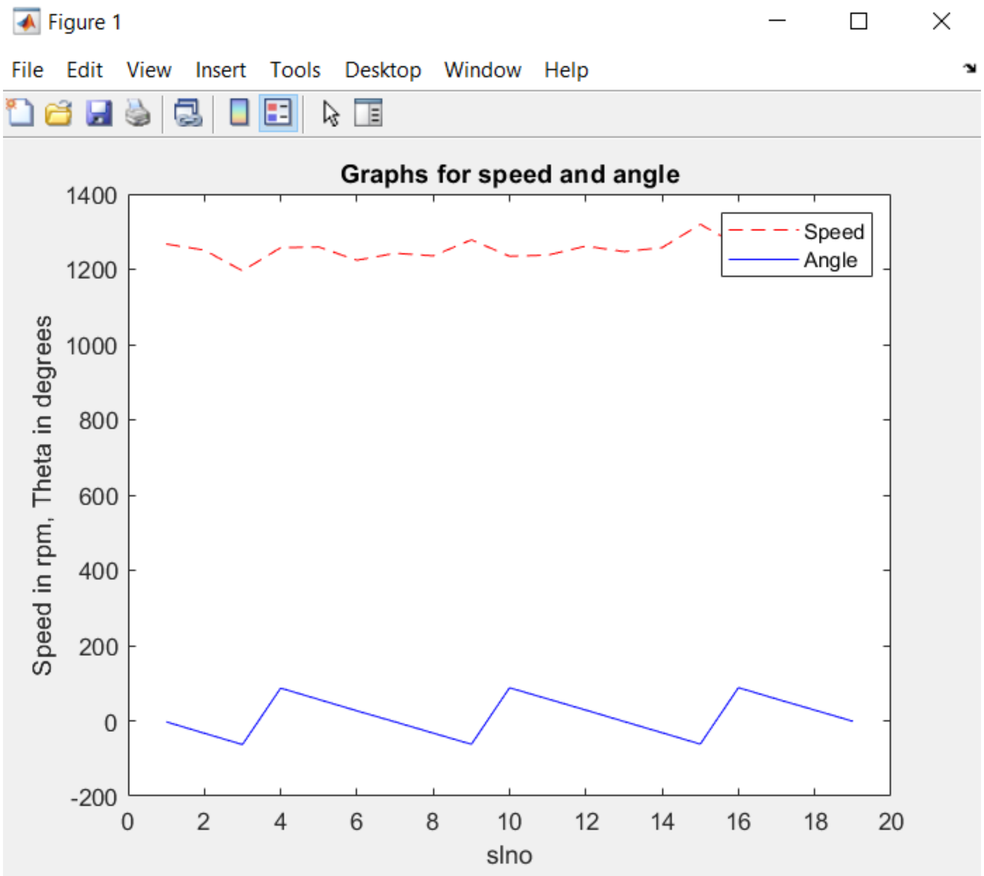
Avg. Speed = 1198.6 rpm

Mean error = 17.1653 rpm

Standard Deviation = 13.4280 rpm

- Medium setting, 250 fps

Frame Count	X Coordinate	Y Coordinate
204	223	630
205	266	780
206	367	781
207	500	872
208	632	902
209	724	861
210	751	757
211	714	652
212	611	492
213	476	400
214	346	371
215	256	412



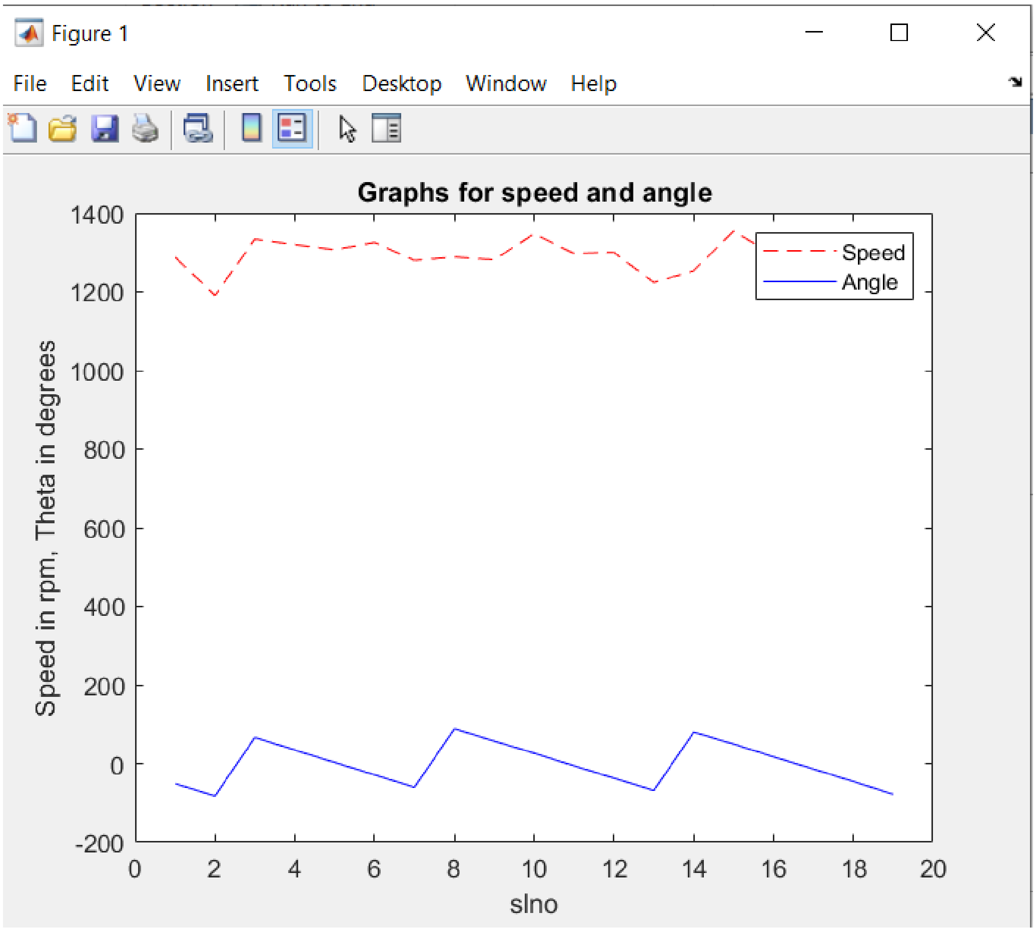
Avg. Speed = 1250 rpm

Mean error = 18.3837 rpm

Standard Deviation = 17.0670 rpm

- High setting, 250 fps

Frame Count	X Coordinate	Y Coordinate
250	654	430
251	523	375
252	381	396
253	268	488
254	225	625
255	256	763
256	355	868
257	494	902
258	621	861
259	724	757
260	753	611
261	699	478



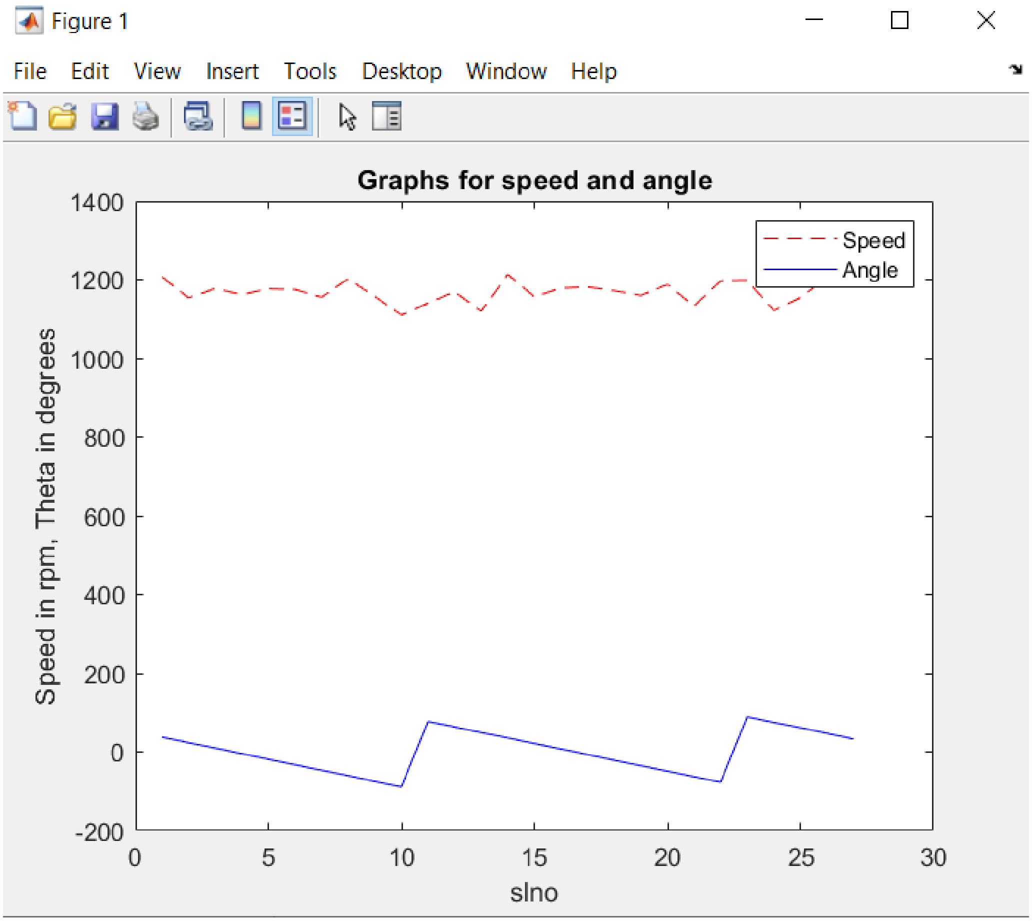
Avg. Speed = 1297.4 rpm

Mean error = 30.9407 rpm

Standard Deviation = 27.4406 rpm

- Low setting, 500 fps

Frame Count	X Coordinate	Y Coordinate
1013	277	474
1014	246	533
1015	226	593
1016	223	658
1017	238	720
1018	264	779
1019	303	831
1020	357	865
1021	416	896
1022	480	904
1023	545	896
1024	605	876



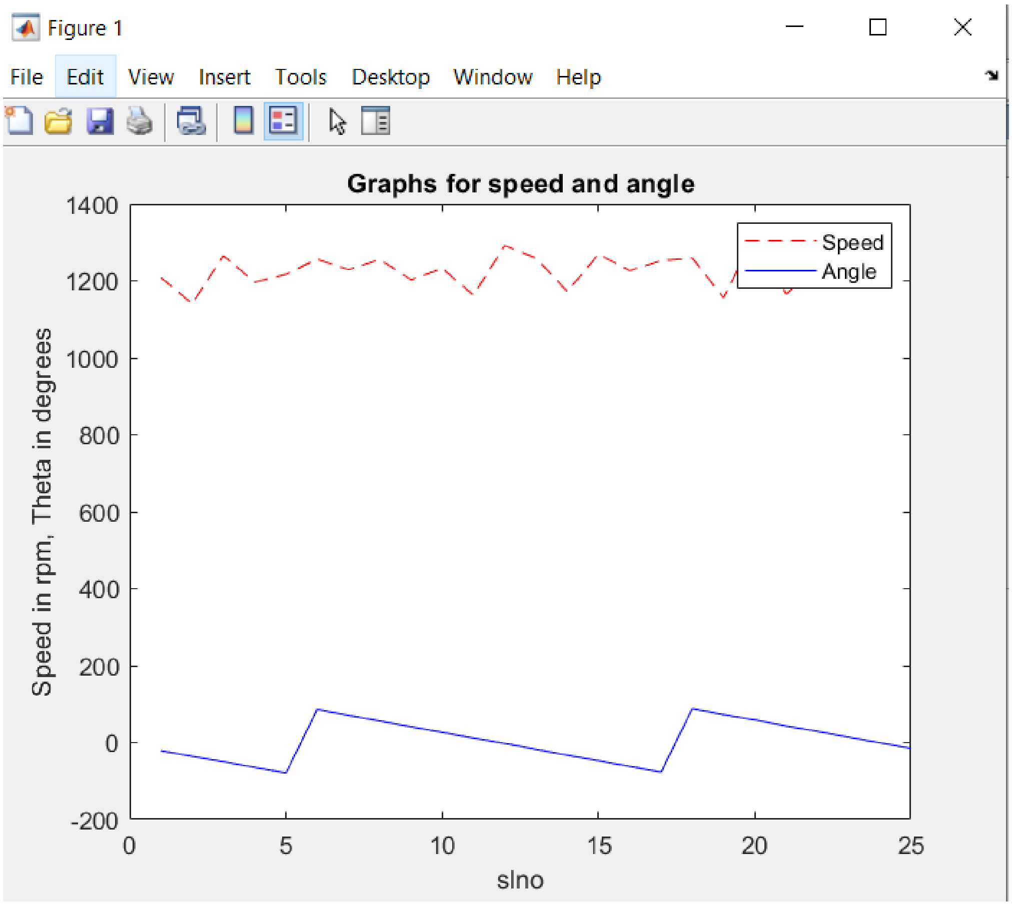
Avg. Speed = 1168.2 rpm

Mean error = 22.4474 rpm

Standard Deviation = 15.8891 rpm

- Medium setting, 500 fps

Frame Count	X Coordinate	Y Coordinate
849	736	541
850	703	482
851	660	435
852	601	396
853	537	377
854	467	373
855	398	385
856	338	418
857	287	465
858	248	519
859	227	584
860	223	648



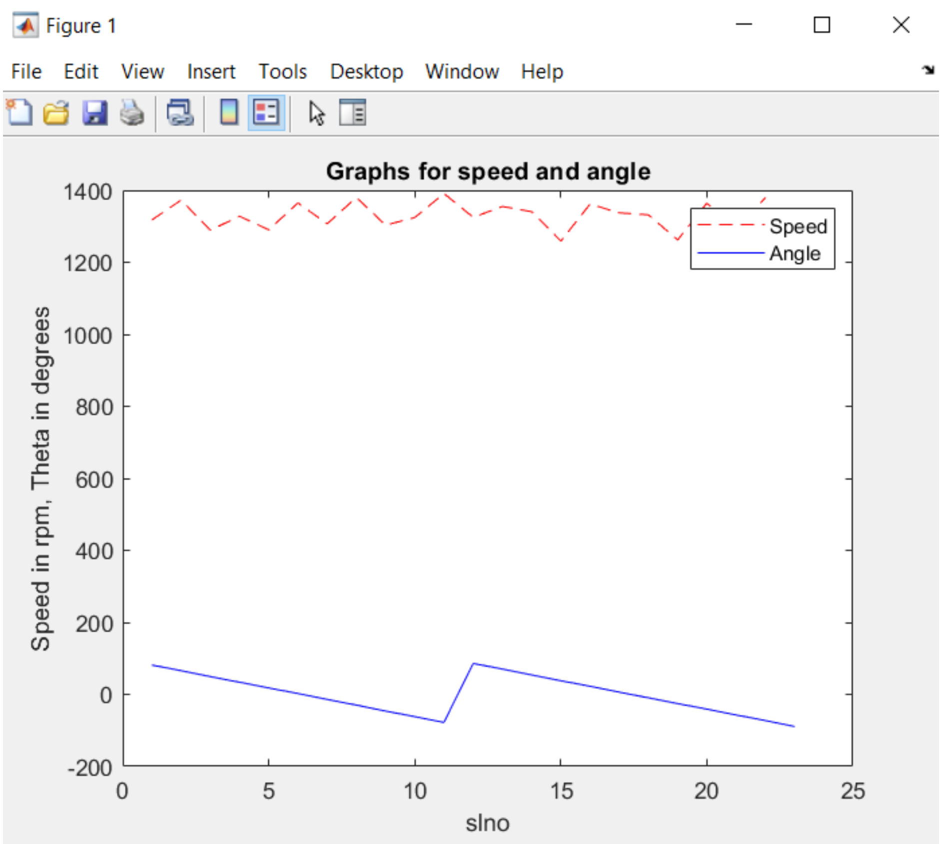
Avg. Speed = 1266 rpm

Mean error = 34.9047 rpm

Standard Deviation = 26.2706 rpm

- High setting, 500 fps

Frame Count	X Coordinate	Y Coordinate
324	521	373
325	447	375
326	377	396
327	313	437
328	268	492
329	238	558
330	223	627
331	233	701
332	256	769
334	303	829
335	363	868
336	430	896



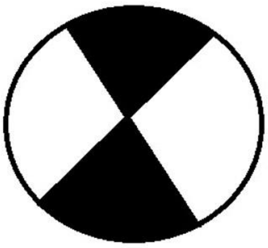
Avg. Speed = 1330.5 rpm

Mean error = 31.2807 rpm

Standard Deviation = 20.7616 rpm

ANALYSIS OF TRANSLATIONAL MOTION

Description – A quad was pasted on an object which was subjected to free fall. The motion was captured using a Fast camera and the acceleration of motion was calculated which ideally should come out as g (9.81 m/s^2).



(Quad)

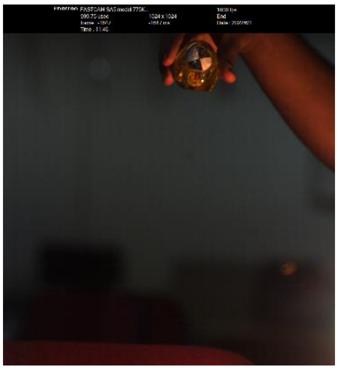
The motion was captured using Photron FastCam viewer in 1000 frames per secs. The coordinates of the centre of the quad was recorded frame by frame. The coordinates were used to calculate the distance traversed in a particular time period which was then used to calculate the velocity and acceleration for the same time period.

Length of the object = 4.6 cm

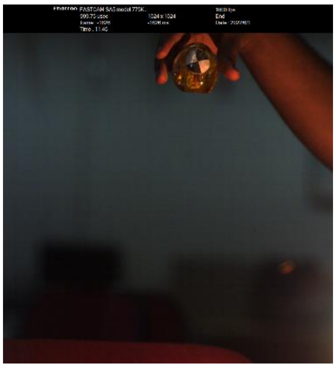
Pixel difference = 149

So, 1 pixel = $\frac{4.6}{149} \times 10^{-2}$ m = 0.03087×10^{-2}m, which is the **scale factor.**

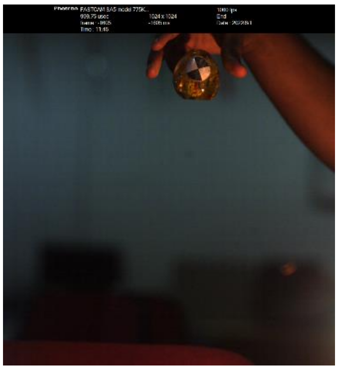
SNAPSHOTS AT DIFFERENT FRAMES



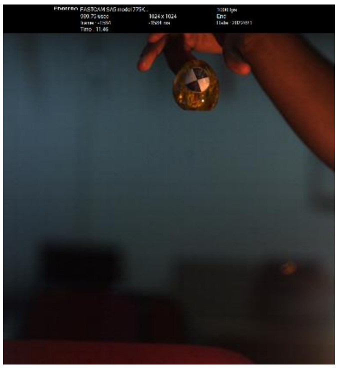
Frame count -1647



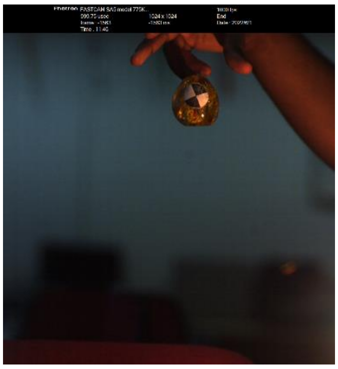
Frame count -1633



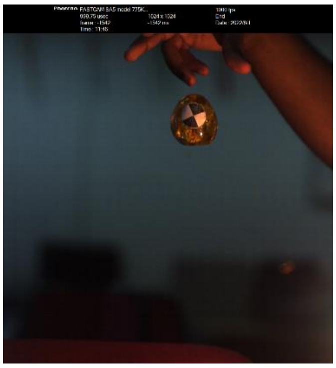
Frame count -1619



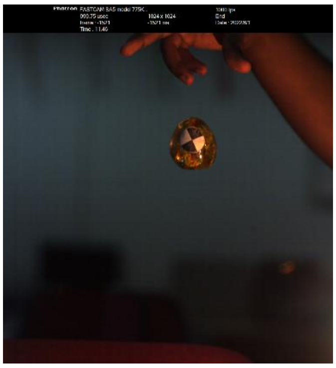
Frame count -1605



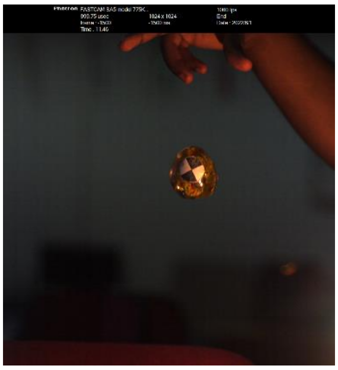
Frame count -1591



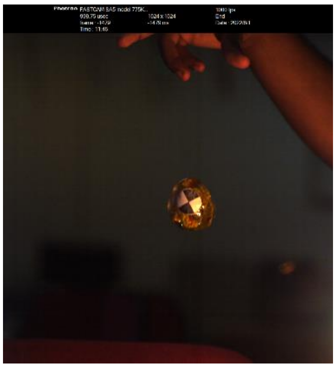
Frame count -1577



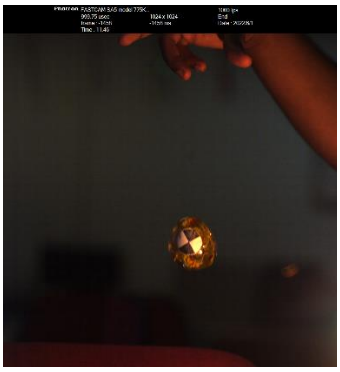
Frame count -1563



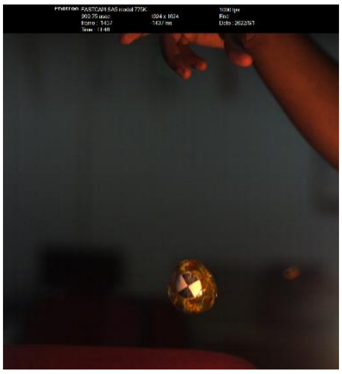
Frame Count -1549



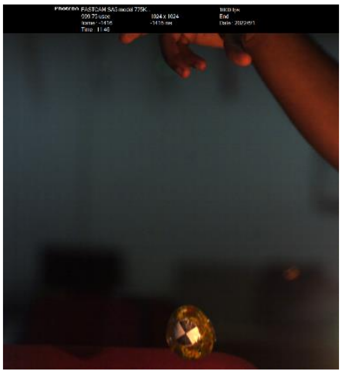
Frame count -1535



Frame count -1521



Frame count -1507



Frame count -1493

MATLAB CODES

Fixing the constants an the coordinates

```
%% Constants
lengt = 4.6e-2;
pixDiff = 149;
sFactor = lengt/pixDiff;
n = 35;
frameDiff = 7;
fps = 1000;
t = [0:frameDiff/fps:((n-3)*frameDiff)/fps];
trueVal = 9.81;

%% Initializing x-coordinate vector, y-coordinate vector, velocity vector and acceleration vector
xVec = [604;604;604;604;604;602;600;598;598;596;596;594;592;592;590;590;
    588;588;584;584;582;578;576;574;574;570;570;568;566;564;560;558;558;554;552];
yVec = [166.778;169.1113;173;178.45;185.45;194.005;204.1151;215.7809;229.002;243.779;260.1106;278;
    297.442;318.4399;341;365.1028;390.7674;417.9874;446.7629;477.0938;508.9801;542.4221;577.4193;
    613.9719;652.0799;691.744;732.9624;775.7367;820.0665;865.97;913.4098;962.4046;1012.9544;1065.0592;1118.719
displ = zeros(n-1,1);
displm = zeros(n-1,1);
vel = zeros((n-1),1);
accln = zeros((n-2),1);
displacement1 = zeros((n-2),1);
```

Computation of the required parameters

```
%% Computation of velocity vector
for i =1:(n-1)
    displ(i) = sqrt((xVec(i+1) - xVec(i))^2 + (yVec(i+1) - yVec(i))^2);
    displm(i) = sFactor*displ(i);
    vel(i) = sFactor*(displ(i)/(frameDiff*(1/fps)));
    % disp(['The value of velocity in m/s is : ', num2str(vel(i))]);
end

%% Computation of acceleration vector
for i = 1:(n-2)
    accln(i) = (vel(i+1) - vel(i))/(frameDiff*(1/fps));
    % disp(['The value of acceleration in m/s^2 is : ', num2str(accln(i))]);
end

%% Calculation of displacement vector
for i = 1:(n-2)
    displacement1(i) = 0.5*accln(i)*t(i)^2;
end
```

Code for plots of the parameters calculated

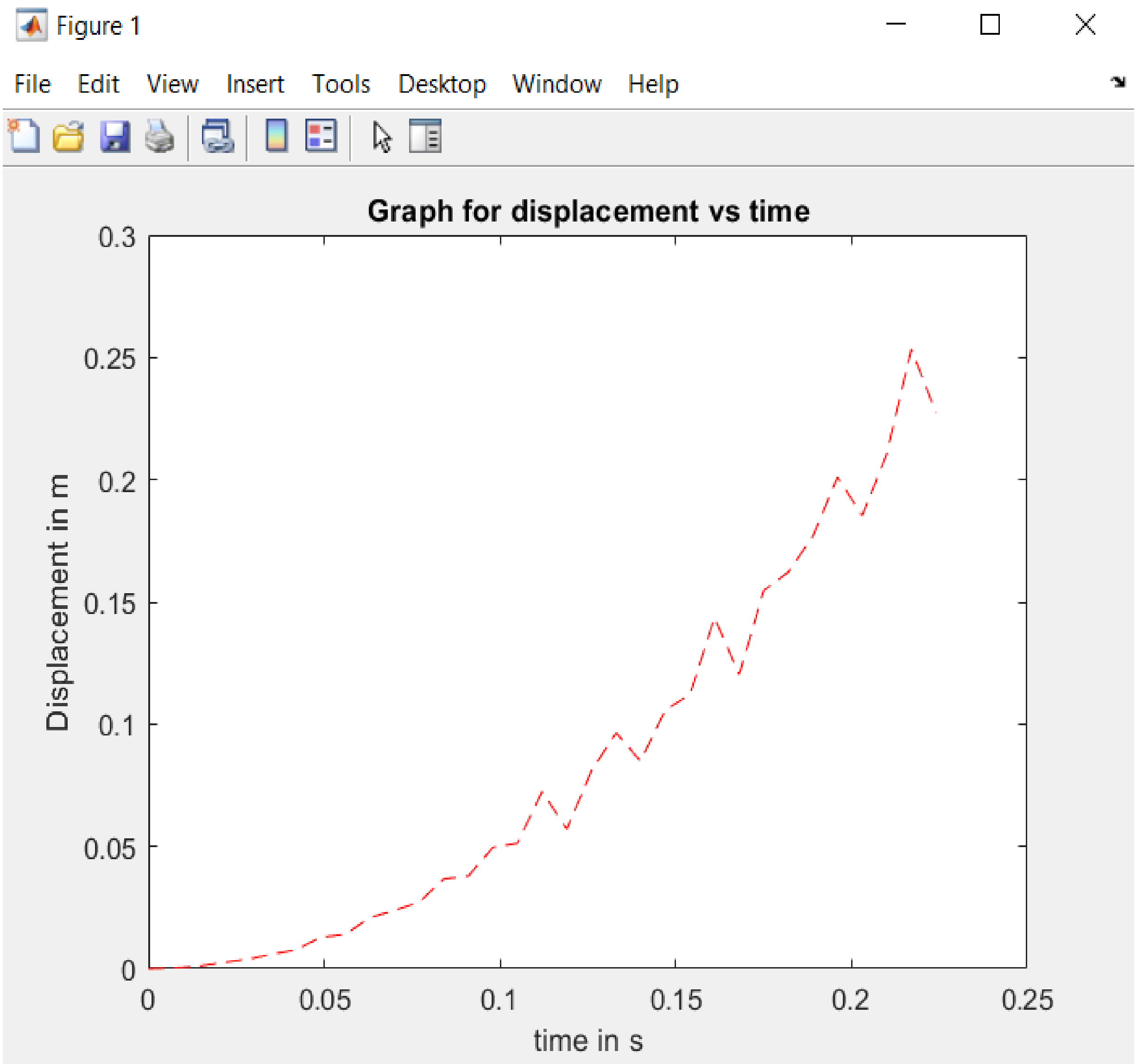
```
%% Plot of displacement vs time, velocity vs time, acceleration vs time
plot(t,displacement1,'--r');
xlabel('time in s');
ylabel('Displacement in m');
title('Graph for displacement vs time');
hold on
t = [0:frameDiff/fps:((n-2)*frameDiff)/fps];
plot(t,vel,'-b');
xlabel('time in s');
ylabel('Velocity in m/s');
title('Graph for velocity vs time');
hold on
t = [0:frameDiff/fps:((n-3)*frameDiff)/fps];
plot(t,accln,'g');
xlabel('time in s');
ylabel('Acceleration in m/s^2');
title('Graph for acceleration vs time');
shg
```

Calculation of Mean, Error, Standard Deviation

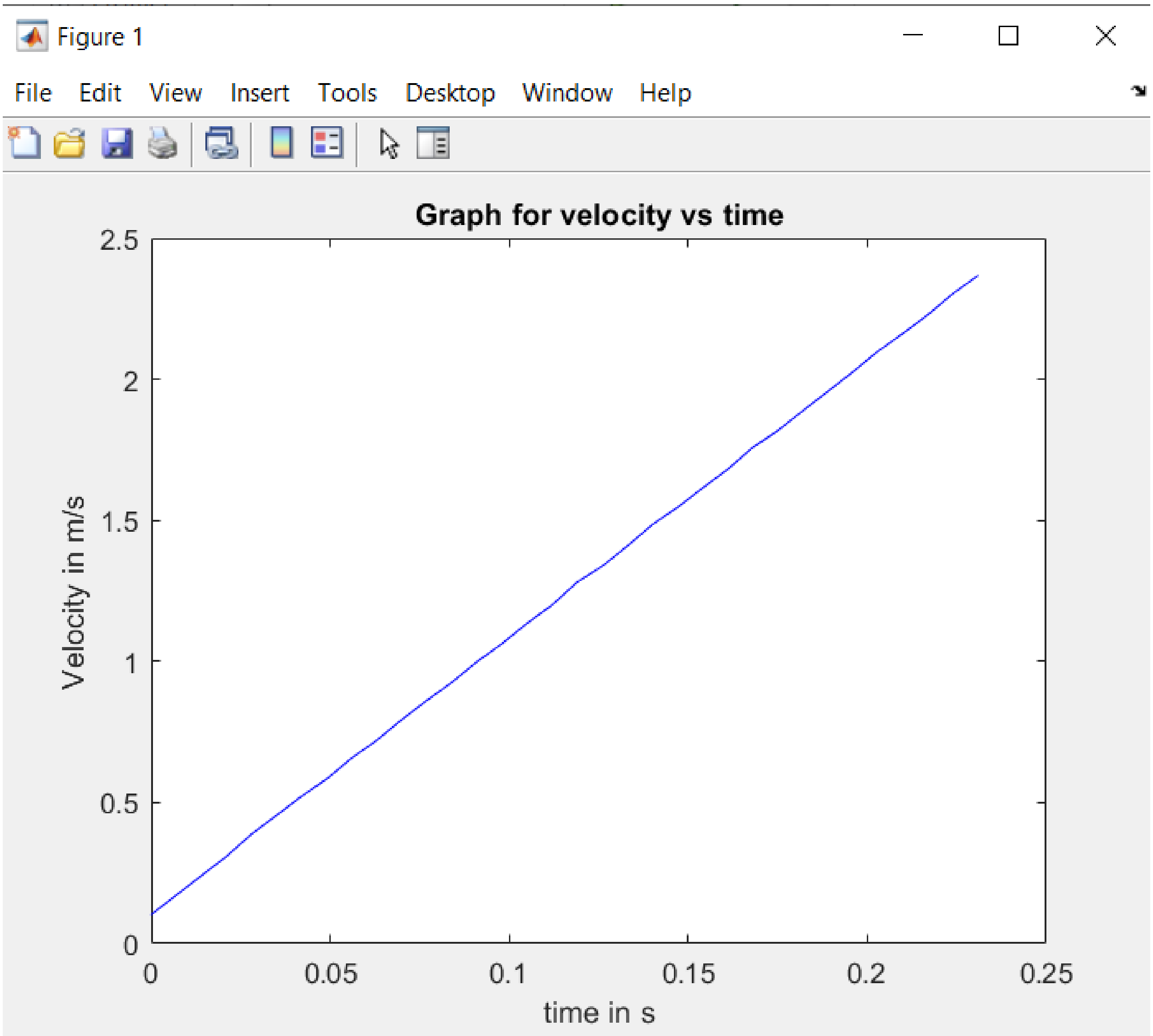
```
%% Calculation of average acceleration
avgAccln = sum(accln)/(n-2);

%% Calculation of error
err = abs(accln-trueVal);

%% Calculation of mean & standard deviation of error
meanErr = sum(err)/(n-2);
VarianceErr = ((sum((err).^2))/(n-2)) -meanErr^2  ;
stndDevitnErr = sqrt(VarianceErr);

%% Display results

% disp(displacement1)
% disp(vel)
% disp(accln)
disp(meanErr);
disp(stndDevitnErr);
```

Plots obtained

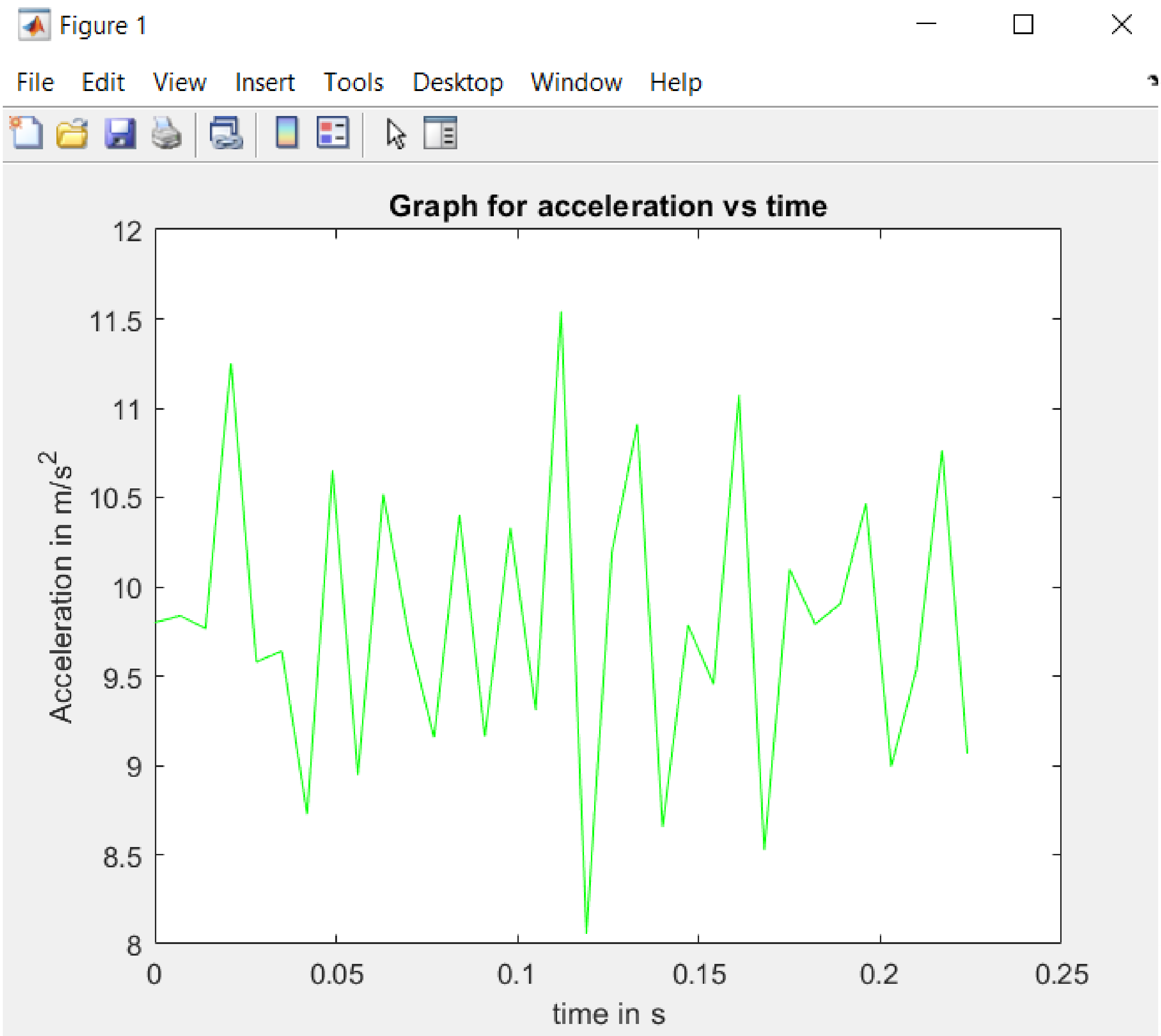
Displacement vs Time



Velocity vs Time



Acceleration vs Time



Avg. acceleration = 9.8066 m/s^2

Mean Error = 0.6457 m/s^2

Standard Deviation = 0.4958 m/s^2

Conclusion

We learnt about the history of imaging and camera and the process of **high speed imaging** and the usage of **high speed cameras** (primarily used for measurement of ballistic parameters at PXE, DRDO) and various sensors developed for imaging. Simultaneously we have successfully completed 2 projects where we could find out the **rpm** of a rotating object and **acceleration due to gravity** for a falling object, respectively. The snapshots of the conducted experiments, the algorithms used for calculating the above parameters and the results obtained have been attached.