Image processing

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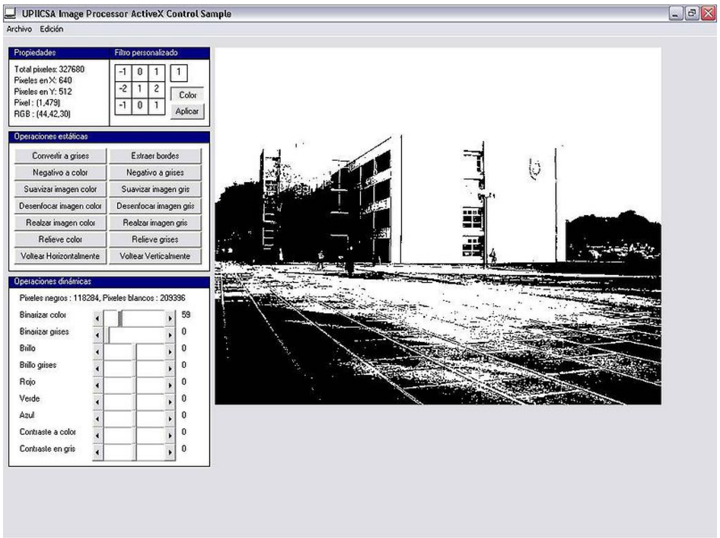
In electrical engineering and computer science, **image processing** is any form of signal processing for which the input is an image, such as photographs or frames of video; the output of image processing can be either an image or a set of characteristics or parameters related to the image. Most image-processing techniques involve treating the image as a two-dimensional signal and applying standard signal-processing techniques to it.



Monochrome black/white image

Image processing usually refers to digital image processing, but optical and analog image processing are also possible. This article is about general techniques that apply to all of them. The *acquisition* of images (producing the input image in the first place) is referred to as imaging.

Typical operations

Among many other image processing operations are:


The red, green, and blue color channels of a photograph by Sergei Mikhailovich Prokudin-Gorskii. The fourth image is a composite.

- Euclidean geometry transformations such as enlargement, reduction, and rotation
- Color corrections such as brightness and contrast adjustments, color mapping, color balancing, quantization, or color translation to a different color space
- Digital compositing or optical compositing (combination of two or more images). Used in film-making to make a "matte"
- Interpolation, demosaicing, and recovery of a full image from a raw image format using a Bayer filter pattern
- Image registration, the alignment of two or more images
- Image differencing and morphing
- Image recognition, for example, extract the text from the image using optical character recognition or checkbox and bubble values using optical mark recognition
- Image segmentation
- High dynamic range imaging by combining multiple images
- Geometric hashing for 2-D object recognition with affine invariance

Applications

- Computer vision
- Optical sorting
- Augmented Reality
- Face detection
- Feature detection
- Lane departure warning system
- Non-photorealistic rendering
- Medical image processing
- Microscope image processing
- Morphological image processing
- Remote sensing

See also

- Imaging
- Photo manipulation
- List of image analysis software
- Near sets
- Multidimensional systems

Further reading

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External links

- Lectures on Image Processing [3], by Alan Peters. Vanderbilt University. Updated 28 April 2008.
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- Image processing algorithms, implementations and demonstrations [5]

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Digital image processing

Digital image processing is the use of computer algorithms to perform image processing on digital images. As a subfield of digital signal processing, digital image processing has many advantages over analog image processing; it allows a much wider range of algorithms to be applied to the input data, and can avoid problems such as the build-up of noise and signal distortion during processing. Since images are defined over two dimensions (perhaps more) digital image processing can be modeled in the form of Multidimensional Systems.

History

Many of the techniques of digital image processing, or digital picture processing as it was often called, were developed in the 1960s at the Jet Propulsion Laboratory, MIT, Bell Labs, University of Maryland, and a few other places, with application to satellite imagery, wirephoto standards conversion, medical imaging, videophone, character recognition, and photo enhancement.[1] But the cost of processing was fairly high with the computing equipment of that era. In the 1970s, digital image processing proliferated, when cheaper computers and dedicated hardware became available. Images could then be processed in real time, for some dedicated problems such as television standards conversion. As general-purpose computers became faster, they started to take over the role of dedicated hardware for all but the most specialized and compute-intensive operations.

With the fast computers and signal processors available in the 2000s, digital image processing has become the most common form of image processing, and is generally used because it is not only the most versatile method, but also the cheapest.

Digital image processing technology for medical applications was inducted into the Space Foundation Space Technology Hall of Fame in 1994.[2]

Tasks

Digital image processing allows the use of much more complex algorithms for image processing, and hence can offer both more sophisticated performance at simple tasks, and the implementation of methods which would be impossible by analog means.

In particular, digital image processing is the only practical technology for:

- Classification
- Feature extraction
- Pattern recognition
- Projection
- Multi-scale signal analysis

Some techniques which are used in digital image processing include:

- Pixelization
- Linear filtering
- Principal components analysis
- Independent component analysis
- Hidden Markov models
- Partial differential equations
- Self-organizing maps
- Neural networks
- Wavelets

Applications

Digital camera images

Digital cameras generally include dedicated digital image processing chips to convert the raw data from the image sensor into a color-corrected image in a standard image file format. Images from digital cameras often receive further processing to improve their quality, a distinct advantage digital cameras have over film cameras. The digital image processing is typically done by special software programs that can manipulate the images in many ways.

Many digital cameras also enable viewing of histograms of images, as an aid for the photographer to better understand the rendered brightness range of each shot.

Film

Westworld (1973) was the first feature film to use digital image processing to pixellate photography to simulate an android's point of view.[3]

See also

- Computer graphics
- Computer vision
- Digitizing
- Endrov
- GPGPU
- ImageJ
- FIJI (software)
- Homomorphic filtering
- OpenCV
- Standard test image
- Super-resolution
- Multidimensional systems

Further reading

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External links

- Tutorial for image processing [4] (contains a Java applet)
- Image processing algorithms, implementations and demonstrations [5]

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Digital imaging

Digital imaging or **digital image acquisition** is the creation of digital images, typically from a physical scene. The term is often assumed to imply or include the processing, compression, storage, printing, and display of such images.

History

Digital imaging was developed in the 1960s and 1970s, largely to avoid the operational weaknesses of film cameras, for scientific and military missions including the KH-11 program. As digital technology became cheaper in later decades it replaced the old film methods for many purposes.

Descriptions

A digital image may be created directly from a physical scene by a camera or similar devices. Alternatively, it may be obtained from another image in an analog medium, such as photographs, photographic film, or printed paper, by an image scanner or similar device. Many technical images—such as those acquired with tomographic equipment, side-scan sonar, or radio telescopes—are actually obtained by complex processing of non-image data. This digitalization of analog real-world data is known as digitizing, and involves sampling (discretization) and quantization.

Finally, a digital image can also be computed from a geometric model or mathematical formula. In this case the name **image synthesis** is more appropriate, and it is more often known as rendering.

Digital image authentication is an emerging issue for the providers and producers of high resolution digital images such as health care organizations, law enforcement agencies and insurance companies. There are methods emerging in forensic science to analyze a digital image and determine if it has been altered.

See also

- Digital image processing
- Digital photography
- Dynamic imaging
- Image editing
- Image retrieval
- Graphics file format
- Graphic image development
- Society for Imaging Science and Technology, (IS&T)
- Film recorder

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Medical imaging

Medical imaging is the technique and process used to create images of the human body (or parts and function thereof) for clinical purposes (medical procedures seeking to reveal, diagnose or examine disease) or medical science (including the study of normal anatomy and physiology). Although imaging of removed organs and tissues can be performed for medical reasons, such procedures are not usually referred to as medical imaging, but rather are a part of pathology.

As a discipline and in its widest sense, it is part of biological imaging and incorporates radiology (in the wider sense), nuclear medicine, investigative radiological sciences, endoscopy, (medical) thermography, medical photography and microscopy (e.g. for human pathological investigations).

Measurement and recording techniques which are not primarily designed to produce images, such as electroencephalography (EEG), magnetoencephalography (MEG), Electrocardiography (EKG) and others, but which produce data susceptible to be represented as maps (i.e. containing positional information), can be seen as forms of medical imaging.

Overview

In the clinical context, medical imaging is generally equated to radiology or "clinical imaging" and the medical practitioner responsible for interpreting (and sometimes acquiring) the images is a radiologist. Diagnostic radiography designates the technical aspects of medical imaging and in particular the acquisition of medical images. The *radiographer* or *radiologic technologist* is usually responsible for acquiring medical images of diagnostic quality, although some radiological interventions are performed by radiologists. While radiology is an evaluation of anatomy, nuclear medicine provides functional assessment.

As a field of scientific investigation, medical imaging constitutes a sub-discipline of biomedical engineering, medical physics or medicine depending on the context: Research and development in the area of instrumentation, image acquisition (e.g. radiography), modelling and quantification are usually the preserve of biomedical engineering, medical physics and computer science; Research into the application and interpretation of medical images is usually the preserve of radiology and the medical sub-discipline relevant to medical condition or area of medical science (neuroscience, cardiology, psychiatry, psychology, etc) under investigation. Many of the techniques developed for medical imaging also have scientific and industrial applications.

Medical imaging is often perceived to designate the set of techniques that noninvasively produce images of the internal aspect of the body. In this restricted sense, medical imaging can be seen as the solution of mathematical inverse problems. This means that cause (the properties of living tissue) is inferred from effect (the observed signal). In the case of ultrasonography the probe consists of ultrasonic pressure waves and echoes inside the tissue show the internal structure. In the case of projection radiography, the probe is X-ray radiation which is absorbed at different rates in different tissue types such as bone, muscle and fat.

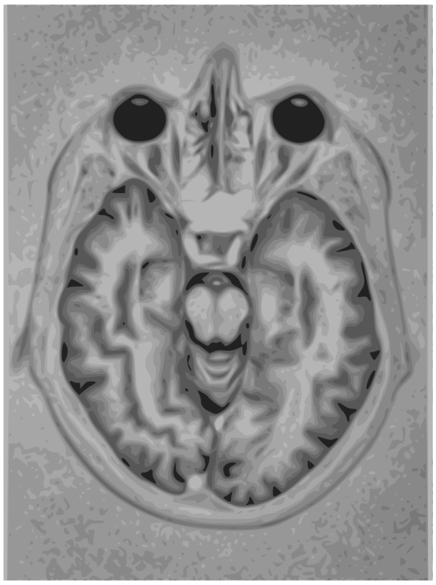
Imaging technology

Radiography

Two forms of radiographic images are in use in medical imaging; projection radiography and fluoroscopy, with the latter being useful for intraoperative and catheter guidance. These 2D techniques are still in wide use despite the advance of 3D tomography due to the low cost, high resolution, and depending on application, lower radiation dosages. This imaging modality utilizes a wide beam of x rays for image acquisition and is the first imaging technique available in modern medicine.

- *Fluoroscopy* produces real-time images of internal structures of the body in a similar fashion to radiography, but employs a constant input of x-rays, at a lower dose rate. Contrast media, such as barium, iodine, and air are used to visualize internal organs as they work. Fluoroscopy is also used in image-guided procedures when constant feedback during a procedure is required. An image receptor is required to convert the radiation into an image after it has passed through the area of interest. Early on this was a fluorescing screen, which gave way to an Image Amplifier (IA) which was a large vacuum tube that had the receiving end coated with cesium iodide, and a mirror at the opposite end. Eventually the mirror was replaced with a TV camera.
- *Projectional radiographs*, more commonly known as x-rays, are often used to determine the type and extent of a fracture as well as for detecting pathological changes in the lungs. With the use of radio-opaque contrast media, such as barium, they can also be used to visualize the structure of the stomach and intestines - this can help diagnose ulcers or certain types of colon cancer.

Magnetic resonance imaging (MRI)


A brain MRI representation

A magnetic resonance imaging instrument (MRI scanner), or "nuclear magnetic resonance (NMR) imaging" scanner as it was originally known, uses powerful magnets to polarise and excite hydrogen nuclei (single proton) in water molecules in human tissue, producing a detectable signal which is spatially encoded, resulting in images of the body. MRI uses three electromagnetic fields: a very strong (on the order of units of teslas) static magnetic field to polarize the hydrogen nuclei, called the static field; a weaker time-varying (on the order of 1 kHz) field(s) for spatial encoding, called the gradient field(s); and a weak radio-frequency (RF) field for manipulation of the hydrogen nuclei to produce measurable signals, collected through an RF antenna.

Like CT, MRI traditionally creates a two dimensional image of a thin "slice" of the body and is therefore considered a tomographic imaging technique. Modern MRI instruments are capable of producing images in the form of 3D blocks, which may be considered a generalisation of the single-slice, tomographic, concept. Unlike CT, MRI does not involve the use of ionizing radiation and is therefore not associated with the same health hazards. For example, because MRI has only been in use since the early 1980s, there are no known long-term effects of exposure to strong static fields (this is the subject of some debate; see 'Safety' in MRI) and therefore there is no limit to the number of scans to which an individual can be subjected, in contrast with X-ray and CT. However, there are well-identified health risks associated with tissue heating from exposure to the RF field and the presence of implanted devices in the body, such as pace makers. These risks are strictly controlled as part of the design of the instrument and the scanning protocols used.

Because CT and MRI are sensitive to different tissue properties, the appearance of the images obtained with the two techniques differ markedly. In CT, X-rays must be blocked by some form of dense tissue to create an image, so the image quality when looking at soft tissues will be poor. In MRI, while any nucleus with a net nuclear spin can be used, the proton of the hydrogen atom remains the most widely used, especially in the clinical setting, because it is so ubiquitous and returns a large signal. This nucleus, present in water molecules, allows the excellent soft-tissue contrast achievable with MRI.

Nuclear medicine

Nuclear medicine encompasses both diagnostic imaging and treatment of disease, and may also be referred to as molecular medicine or molecular imaging & therapeutics [1] . Nuclear medicine uses certain properties of isotopes and the energetic particles emitted from radioactive material to diagnose or treat various pathology. Different from the typical concept of anatomic radiology, nuclear medicine enables assessment of physiology. This function-based approach to medical evaluation has useful applications in most subspecialties, notably oncology, neurology, and cardiology. *Gamma cameras* are used in e.g. scintigraphy, SPECT and PET to detect regions of biologic activity that may be associated with disease. Relatively short lived isotope, such as ^{123}I is administered to the patient. Isotopes are often preferentially absorbed by biologically active tissue in the body, and can be used to identify tumors or fracture points in bone. Images are acquired after collimated photons are detected by a crystal that gives off a light signal, which is in turn amplified and converted into count data.

- *Scintigraphy* ("scint") is a form of diagnostic test wherein radioisotopes are taken internally, for example intravenously or orally. Then, gamma camera capture and form two-dimensional[2] images from the radiation emitted by the radiopharmaceuticals.

- *SPECT* is a 3D tomographic technique that uses gamma camera data from many projections and can be reconstructed in different planes. A dual detector head gamma camera combined with a CT scanner, which provides localization of functional SPECT data, is termed a SPECT/CT camera, and has shown utility in advancing the field of molecular imaging.
- *Positron emission tomography* (PET) uses coincidence detection to image functional processes. Short-lived positron emitting isotope, such as ^{18}F, is incorporated with an organic substance such as glucose, creating F18-fluorodeoxyglucose, which can be used as a marker of metabolic utilization. Images of activity distribution throughout the body can show rapidly growing tissue, like tumor, metastasis, or infection. PET images can be viewed in comparison to computed tomography scans to determine an anatomic correlate. Modern scanners combine PET with a CT, or even MRI, to optimize the image reconstruction involved with positron imaging. This is performed on the same equipment without physically moving the patient off of the gantry. The resultant hybrid of functional and anatomic imaging information is a useful tool in non-invasive diagnosis and patient management.

Photoacoustic imaging

Photoacoustic imaging is a recently developed hybrid biomedical imaging modality based on the photoacoustic effect. It combines the advantages of optical absorption contrast with ultrasonic spatial resolution for deep imaging in (optical) diffusive or quasi-diffusive regime. Recent studies have shown that photoacoustic imaging can be used in vivo for tumor angiogenesis monitoring, blood oxygenation mapping, functional brain imaging, and skin melanoma detection, etc.

Breast Thermography

Digital infrared imaging thermography is based on the principle that metabolic activity and vascular circulation in both pre-cancerous tissue and the area surrounding a developing breast cancer is almost always higher than in normal breast tissue. Cancerous tumors require an ever-increasing supply of nutrients and therefore increase circulation to their cells by holding open existing blood vessels, opening dormant vessels, and creating new ones (neoangiogenesis). This process frequently results in an increase in regional surface temperatures of the breast. Digital infrared imaging uses extremely sensitive medical infrared cameras and sophisticated computers to detect, analyze, and produce high-resolution diagnostic images of these temperature variations. Because of DII's sensitivity, these temperature variations may be among the earliest signs of breast cancer and/or a pre-cancerous state of the breast[3] .

Tomography

Tomography is the method of imaging a single plane, or slice, of an object resulting in a tomogram. There are several forms of tomography:

- Linear tomography: This is the most basic form of tomography. The X-ray tube moved from point "A" to point "B" above the patient, while the cassette holder (or "bucky") moves simultaneously under the patient from point "B" to point "A." The fulcrum, or pivot point, is set to the area of interest. In this manner, the points above and below the focal plane are blurred out, just as the background is blurred when panning a camera during exposure. No longer carried out and replaced by computed tomography.
- Poly tomography: This was a complex form of tomography. With this technique, a number of geometrical movements were programmed, such as hypocycloidic, circular, figure 8, and elliptical. Philips Medical Systems [4] produced one such device called the 'Polytome.' This unit was still in use into the 1990s, as its resulting images for small or difficult physiology, such as the inner ear, was still difficult to image with CTs at that time. As the resolution of CTs got better, this procedure was taken over by the CT.

- Zonography: This is a variant of linear tomography, where a limited arc of movement is used. It is still used in some centres for visualising the kidney during an intravenous urogram (IVU).
- Orthopantomography (OPT or OPG): The only common tomographic examination in use. This makes use of a complex movement to allow the radiographic examination of the mandible, as if it were a flat bone. It is often referred to as a "Panorex", but this is incorrect, as it is a trademark of a specific company.
- Computed Tomography (CT), or Computed Axial Tomography (CAT: A CT scan, also known as a CAT scan, is a helical tomography (latest generation), which traditionally produces a 2D image of the structures in a thin section of the body. It uses X-rays. It has a greater ionizing radiation dose burden than projection radiography; repeated scans must be limited to avoid health effects.

Ultrasound

Medical ultrasonography uses high frequency broadband sound waves in the megahertz range that are reflected by tissue to varying degrees to produce (up to 3D) images. This is commonly associated with imaging the fetus in pregnant women. Uses of ultrasound are much broader, however. Other important uses include imaging the abdominal organs, heart, breast, muscles, tendons, arteries and veins. While it may provide less anatomical detail than techniques such as CT or MRI, it has several advantages which make it ideal in numerous situations, in particular that it studies the function of moving structures in real-time, emits no ionizing radiation, and contains speckle that can be used in elastography. It is very safe to use and does not appear to cause any adverse effects, although information on this is not well documented. It is also relatively inexpensive and quick to perform. Ultrasound scanners can be taken to critically ill patients in intensive care units, avoiding the danger caused while moving the patient to the radiology department. The real time moving image obtained can be used to guide drainage and biopsy procedures. Doppler capabilities on modern scanners allow the blood flow in arteries and veins to be assessed.

Medical imaging topics

Maximizing imaging procedure use

The amount of data obtained in a single MR or CT scan is very extensive. Some of the data that radiologists discard could save patients time and money, while reducing their exposure to radiation and risk of complications from invasive procedures.[5]

Creation of three-dimensional images

Recently, techniques have been developed to enable CT, MRI and ultrasound scanning software to produce 3D images for the physician.[6] Traditionally CT and MRI scans produced 2D static output on film. To produce 3D images, many scans are made, then combined by computers to produce a 3D model, which can then be manipulated by the physician. 3D ultrasounds are produced using a somewhat similar technique. In diagnosing disease of the viscera of abdomen,ultrasound is particularly sensitive on imaging of biliary tract,urinary tract and female reproductive organs(ovary,fallopian tubes).As for example,diagnosis of gall stone by dilatation of common bile duct and stone in common bile duct . With the ability to visualize important structures in great detail, 3D visualization methods are a valuable resource for the diagnosis and surgical treatment of many pathologies. It was a key resource for the famous, but ultimately unsuccessful attempt by Singaporean surgeons to separate Iranian twins Ladan and Laleh Bijani in 2003. The 3D equipment was used previously for similar operations with great success.

Other proposed or developed techniques include:

- Diffuse optical tomography
- Elastography
- Electrical impedance tomography

- Optoacoustic imaging
- Ophthalmology
  - A-scan
  - B-scan
  - Corneal topography
  - Optical coherence tomography
  - Scanning laser ophthalmoscopy

Some of these techniques are still at a research stage and not yet used in clinical routines.

Compression of medical images

Medical imaging techniques produce very large amounts of data, especially from CT, MRI and PET modalities. As a result, storage and communications of electronic image data are prohibitive without the use of compression. JPEG 2000 is the state-of-the-art image compression DICOM standard for storage and transmission of medical images. The cost and feasibility of accessing large image data sets over low or various bandwidths are further addressed by use of another DICOM standard, called JPIP, to enable efficient streaming of the JPEG 2000 compressed image data.

Non-diagnostic imaging

Neuroimaging has also been used in experimental circumstances to allow people (especially disabled persons) to control outside devices, acting as a brain computer interface.

Archiving and recording

Used primarily in ultrasound imaging, capturing the image a medical imaging device is required for archiving and telemedicine applications. In most scenarios, a frame grabber is used in order to capture the video signal from the medical device and relay it to a computer for further processing and operations.[7]

Open source software for medical image analysis

Several open source software packages are available for performing analysis of medical images:

- ImageJ
- 3D Slicer
- ITK
- OsiriX
- GemIdent
- MicroDicom
- FreeSurfer
- FreePlugin

Use in pharmaceutical clinical trials

Medical imaging has become a major tool in clinical trials since it enables rapid diagnosis with visualization and quantitative assessment.

A typical clinical trial goes through multiple phases and can take up to eight years. Clinical endpoints or outcomes are used to determine whether the therapy is safe and effective. Once a patient reaches the endpoint, he/she is generally excluded from further experimental interaction. Trials that rely solely on clinical endpoints are very costly as they have long durations and tend to need large number of patients.

In contrast to clinical endpoints, surrogate endpoints have been shown to cut down the time required to confirm whether a drug has clinical benefits. Imaging biomarkers (a characteristic that is objectively measured by an imaging technique, which is used as an indicator of pharmacological response to a therapy) and surrogate endpoints have shown to facilitate the use of small group sizes, obtaining quick results with good statistical power.[8]

Imaging is able to reveal subtle change that is indicative of the progression of therapy that may be missed out by more subjective, traditional approaches. Statistical bias is reduced as the findings are evaluated without any direct patient contact.

For example, measurement of tumour shrinkage is a commonly used surrogate endpoint in solid tumour response evaluation. This allows for faster and more objective assessment of the effects of anticancer drugs. In evaluating the extent of Alzheimer's disease, it is still prevalent to use behavioural and cognitive tests. MRI scans on the entire brain can accurately pinpoint hippocampal atrophy rate while PET scans is able to measure the brain's metabolic activity by measuring regional glucose metabolism.[8]

An imaging-based trial will usually be made up of three components:

1. A realistic imaging protocol. The protocol is an outline that standardizes (as far as practically possible) the way in which the images are acquired using the various modalities (PET, SPECT, CT, MRI). It covers the specifics in which images are to be stored, processed and evaluated.
2. An imaging centre that is responsible for collecting the images, perform quality control and provide tools for data storage, distribution and analysis. It is important for images acquired at different time points are displayed in a standardised format to maintain the reliability of the evaluation. Certain specialised imaging contract research organizations provide to end medical imaging services, from protocol design and site management through to data quality assurance and image analysis.
3. Clinical sites that recruit patients to generate the images to send back to the imaging centre.

See also

- Preclinical imaging
- Cardiac PET
- Biomedical informatics
- Digital Imaging and Communications in Medicine
- Digital Mammography and PACS
- EMMI European Master in Molecular Imaging
- Fotofinder
- Full-body scan
- VoluMedic
- Magnetic field imaging
- Medical examination
- Medical radiography
- Medical test
- Neuroimaging
- Non-invasive (medical)
- PACS
- JPEG 2000 compression
- JPIP streaming
- Pneumoencephalogram
- Radiology information system
- Segmentation (image processing)
- Signal-to-noise ratio
- Society for Imaging Science and Technology
- Tomogram
- Virtopsy

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- Medical Image Database [13] Free Indexed Online Images
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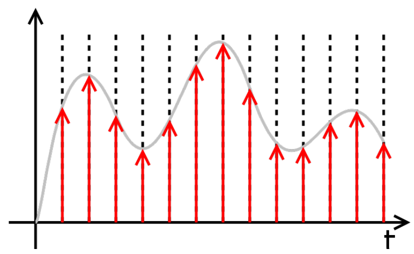
Digital images

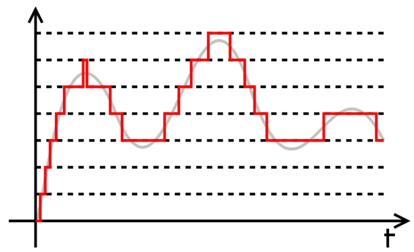
Quantization (signal processing)

In digital signal processing, **quantization** is the process of approximating ("mapping") a continuous range of values (or a very large set of possible discrete values) by a relatively small ("finite") set of ("values which can still take on continuous range") discrete symbols or integer values. For example, rounding a real number in the interval $[0, 100]$ to an integer $0, 1, 2 \ldots, 100$.



Sampled signal (discrete signal): discrete time, continuous values.

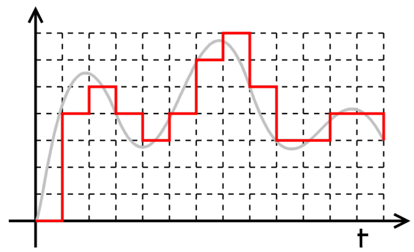
In other words, quantization can be described as a mapping that represents a finite continuous interval $I = [a, b]$ of the range of a continuous valued signal, with a single number *c*, which is also on that interval. For example, rounding to the nearest integer (rounding ½ up) replaces the interval $[c - .5, c + .5)$ with the number *c*, for integer *c*. After that quantization we produce a finite set of values which can be encoded by binary techniques for example.



Quantized signal: continuous time, discrete values.

In signal processing, quantization refers to approximating the *output* by one of a discrete and finite set of values, while replacing the *input* by a discrete set is called *discretization,* and is done by sampling: the resulting sampled signal is called a *discrete signal* (discrete *time*), and need not be quantized (it can have continuous *values*). To produce a digital signal (discrete time and discrete values), one both samples (discrete time) and quantizes the resulting sample values (discrete values).

Applications



Digital signal (sampled, quantized): discrete time, discrete values.

In electronics, adaptive quantization is a quantization process that varies the step size based on the changes of the input signal, as a means of efficient compression. Two approaches commonly used are forward adaptive quantization and backward adaptive quantization.

In signal processing the quantization process is the necessary and natural follower of the sampling operation. It is necessary because in practice the digital computer with its general purpose CPU is used to implement DSP algorithms. And since computers can only process finite word length (finite resolution/precision) quantities, any infinite precision continuous valued signal should be quantized to fit a finite resolution, so that it can be represented (stored) in CPU registers and memory.

We shall be aware of the fact that, it is not the continuous values of the analog function that inhibits its binary encoding, rather it is the existence of infinitely many such values due to the definition of continuity,(which therefore requires infinitely many bits to represent). For example we can design a quantizer such that it represents a signal with a single bit (just two levels) such that, one level is "pi=3,14..." (say encoded with a 1) and the other level is "e=2.7183..." (say encoded with a 0), as we can see, the quantized values of the signal take on infinite precision, irrational numbers. But there are only two levels. And we can represent the output of the quantizer with a binary symbol. Concluding from this we can see that it is not the discreteness of the quantized values that enable them to be encoded but the finiteness enabling the encoding with finite number of bits.

In theory there is no relation between quantization values and binary code words used to encode them (rather than a table that shows the corresponding mapping, just as examplified above). However due to practical reasons we may tend to use code words such that their binary mathematical values has a relation with the quantization levels that is encoded. And this last option merges the first two paragrahs in such a way that, if we wish to process the output of a quantizer within a DSP/CPU system (which is always the case) then we can not allow the representation levels of the quantizers to take on arbitrary values, but only a restricted range such that they can fit in computer registers.

A quantizer is identified with its number of levels M, the decision boundaries {di} and the corresponding representation values {ri}.

The output of a quantizer has two important properties: 1) a Distortion resulting from the approximation and 2) a Bit-Rate resulting from binary encoding of its levels. Therefore the Quantizer design problem is a Rate-Distortion optimization type.

If we are only allowed to use fixed length code for the output level encoding (the practical case) then the problem reduces into a distortion minimization one.

The design of a quantizer usually means the process to find the sets {di} and {ri} such that a measure of optimality is satisfied (such as MMSEQ (Minimum Mean Squared Quantization Error))

Given the number of levels M, the optimal quantizer which minimizes the MSQE with regards to the given signal statistics is called the Max-Lloyd quantizer, which is a non-uniform type in general.

The most common quantizer type is the uniform one. It is simple to design and implement and for most cases it suffices to get satisfactory results. Indeed by the very inherent nature of the design process, a given quantizer will only produce optimal results for the assumed signal statistics. Since it is very difficult to correctly predict that in advance, any static design will never produce actual optimal performance whenever the input statistics deviates from that of the design assumption. The only solution is to use an adaptive quantizer.

External links

- Quantization threads in Comp.DSP [1]
- Signal to quantization noise in quantized sinusoidal [2] - Analysis of quantization error on a sine wave

References

[1] http://www.dsprelated.com/comp.dsp/keyword/Quantization.php
[2] http://www.dsplog.com/2007/03/19/signal-to-quantization-noise-in-quantized-sinusoidal/

Brightness

Brightness is an attribute of visual perception in which a source appears to be radiating or reflecting light.[1] In other words, brightness is the perception elicited by the luminance of a visual target. This is a subjective attribute/property of an object being observed.

Terminology

The adjective *bright* derives from an Old English *beorht* with the same meaning via metathesis giving Middle English *briht*. The word is from a Common Germanic **berhtaz*, ultimately from a PIE root with a closely related meaning, **bhereg-* "white, bright".

"Brightness" was formerly used as a synonym for the photometric term *luminance* and (incorrectly) for the radiometric term *radiance*. As defined by the US *Federal Glossary of Telecommunication Terms* (FS-1037C), "brightness" should now be used only for non-quantitative references to physiological sensations and perceptions of light.[2]

A given target luminance can elicit different perceptions of brightness in different contexts; see, for example, White's illusion and Wertheimer-Benary illusion.

In the RGB color space, brightness can be thought of as the arithmetic mean μ of the red, green, and blue color coordinates (although some of the three components make the light seem brighter than others, which, again, may be compensated by some display systems automatically):[3]

$$\mu = \frac{R+G+B}{3}$$

Brightness is also a color coordinate in the HSB or HSV color space (hue, saturation, and brightness or value).

With regard to stars, brightness is quantified as apparent magnitude and absolute magnitude

Brightness of sounds

The term "brightness" is also used in discussions of sound timbres, in a rough analogy with visual brightness. Timbre researchers consider brightness to be one of the perceptually strongest distinctions between sounds[4] , and formalize it acoustically as an indication of the amount of high-frequency content in a sound, using a measure such as the spectral centroid.

See also

- Luma (video)
- Luminance (relative)
- Luminosity

External links

- Poynton's Color FAQ [5]

References

[1] Merriam-Webster.com (http://www.merriam-webster.com/dictionary/bright) Merriam-Webster Dictionary definition of bright

[2] " Brightness (http://www.its.bldrdoc.gov/fs-1037/dir-005/_0719.htm)" in Federal Standard 1037C, the *Federal Glossary of Telecommunication Terms* (1996)

[3] What are HSB and HLS? (http://www.poynton.com/notes/colour_and_gamma/ColorFAQ.html#RTFToC36), Charles Poynton: "The usual formulation of HSB and HLS compute so-called "lightness" or "brightness" as (R+G+B)/3. This computation conflicts badly with the properties of colour vision, as it computes yellow to be about six times more intense than blue with the same "lightness" value (say L=50)."

[4] D. Wessel, Timbre space as a musical control structure (http://mediatheque.ircam.fr/articles/textes/Wessel78a/), Computer Music Journal, 3 (1979), pp. 45–52.

[5] http://www.poynton.com/ColorFAQ.html

Luminance

Luminance is a photometric measure of the luminous intensity per unit area of light travelling in a given direction. It describes the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle. The SI unit for luminance is candela per square metre (cd/m^2). A non-SI term for the same unit is the "nit". The CGS unit of luminance is the stilb, which is equal to one candela per square centimetre or 10 kcd/m^2.

Luminance is often used to characterize emission or reflection from flat, diffuse surfaces. The luminance indicates how much luminous power will be perceived by an eye looking at the surface from a particular angle of view. Luminance is thus an indicator of how bright the surface will appear. In this case, the solid angle of interest is the solid angle subtended by the eye's pupil. Luminance is used in the video industry to characterize the brightness of displays. A typical computer display emits between 50 and 300 cd/m^2. The sun has luminance of about 1.6×10^9 cd/m^2 at noon.[1]

Luminance is invariant in geometric optics. This means that for an ideal optical system, the luminance at the output is the same as the input luminance. For real, passive, optical systems, the output luminance is *at most* equal to the input. As an example, if you form a demagnified image with a lens, the luminous power is concentrated into a smaller area, meaning that the illuminance is higher at the image. The light at the image plane, however, fills a larger solid angle so the luminance comes out to be the same assuming there is no loss at the lens. The image can never be "brighter" than the source.

Definition

Luminance is defined by

$$L_\mathrm{v} = \frac{\mathrm{d}^2 F}{\mathrm{d}A\,\mathrm{d}\Omega\cos\theta}$$

where

L_v is the luminance (cd/m^2),

F is the luminous flux or luminous power (lm),

θ is the angle between the surface normal and the specified direction,

A is the area of the surface (m^2), and

Ω is the solid angle (sr).

See also

- Diffuse reflection
- Etendue
- Exposure value
- Illuminance
- Lambert
- Lambertian reflectance
- Lightness, property of a color
- Luma, the representation of luminance in a video monitor
- Lumen (unit)
- Radiance

External links

- A Kodak guide to Estimating Luminance and Illuminance [2] using a camera's exposure meter. Also available in PDF form [3] and Google Docs online version [4]

Quantity	Symbol	SI unit	Abbr.	Notes
Luminous energy	Q_v	lumen second	lm·s	units are sometimes called talbots
Luminous flux	F	lumen (= cd·sr)	lm	also called *luminous power*
Luminous intensity	I_v	candela (= lm/sr)	cd	an SI base unit
Luminance	L_v	candela per square metre	cd/m^2	units are sometimes called "nits"
Illuminance	E_v	lux (= lm/m^2)	lx	Used for light incident on a surface
Luminous emittance	M_v	lux (= lm/m^2)	lx	Used for light emitted from a surface
Luminous efficacy		lumen per watt	lm/W	ratio of luminous flux to radiant flux
See also SI · Photometry				

References

[1] "Luminance" (http://www.schorsch.com/kbase/glossary/luminance.html). *Lighting Design Glossary*. . Retrieved Apr. 13, 2009.
[2] http://www.kodak.com/cluster/global/en/consumer/products/techInfo/am105/am105kic.shtml
[3] http://www.kodak.com/cluster/global/en/consumer/products/techInfo/am105/am105kic.pdf
[4] http://docs.google.com/gview?a=v&q=cache:3ygRnO1mEpEJ:www.kodak.com/cluster/global/en/consumer/products/techInfo/am105/am105kic.pdf+estimating+luminance+and+illuminance+with+reflection+type&hl=en&gl=ie&sig=AFQjCNGlsuOrMAs62ZwlzQilxa6mkx0QaA

Contrast (vision)


Left side of the image has low contrast, the right has higher contrast.

Contrast is the difference in visual properties that makes an object (or its representation in an image) distinguishable/darker or brighter from other objects and the background. In visual perception of the real world, contrast is determined by the difference in the color and brightness of the object and other objects within the same field of view. Because the human visual system is more sensitive to contrast than absolute luminance, we can perceive the world similarly regardless of the huge changes in illumination over the day or from place to place.

The human contrast sensitivity function shows a typical band-pass shape peaking at around 4 cycles per degree with sensitivity dropping off either side of the peak.[1] This tells us that the human visual system is most sensitive in detecting contrast differences occurring at 4 cycles per degree, i.e. at this spatial frequency humans can detect lower contrast differences than at any other spatial frequency.


Changes in the amount of contrast in a photo

The high-frequency cut-off represents the optical limitations of the visual system's ability to resolve detail and is typically about 60 cycles per degree. The high-frequency cut-off is related to the packing density of the retinal photoreceptor cells: a finer matrix can resolve finer gratings.

The low frequency drop-off is due to lateral inhibition within the retinal ganglion cells. A typical retinal ganglion cell presents a centre region with either excitation or inhibition and a surround region with the opposite sign. By using coarse gratings, the bright bands fall on the inhibitory as well as the excitatory region of the ganglion cell resulting in lateral inhibition and account for the low-frequency drop-off of the human contrast sensitivity function.

One experimental phenomenon is the inhibition of blue in the periphery if blue light is displayed against white, leading to a yellow surrounding. The yellow is derived from the inhibition of blue on the surroundings by the center. Since white minus blue is red and green, this mixes to become yellow.[2]

For example, in the case of graphical computer displays, contrast depends on the properties of the picture source or file and the properties of the computer display, including its variable settings. For some screens the angle between the screen surface and the observer's line of sight is also important.

Contrast is also the difference between the color or shading of the printed material on a document and the background on which it is printed, for example in optical character recognition.

Formula

There are many possible definitions of contrast. Some include color; others do not. Travnikova laments, "Such a multiplicity of notions of contrast is extremely inconvenient. It complicates the solution of many applied problems and makes it difficult to compare the results published by different authors."[3]

An image of the Notre Dame cathedral as seen from the Eiffel Tower

The same image, with added global contrast, and local contrast (acutance) increased through unsharp masking.

Various definitions of contrast are used in different situations. Here, luminance contrast is used as an example, but the formulas can also be applied to other physical quantities. In many cases, the definitions of contrast represent a ratio of the type

$$\frac{\text{Luminance difference}}{\text{Average luminance}}.$$

The rationale behind this is that a small difference is negligible if the average luminance is high, while the same small difference matters if the average luminance is low (see Weber–Fechner law). Below, some common definitions are given.

Weber contrast

The Weber contrast is defined as

$$\frac{I - I_\mathrm{b}}{I_\mathrm{b}},$$

with I and I_b representing the luminance of the features and the background luminance, respectively. It is commonly used in cases where small features are present on a large uniform background, i.e. the average luminance is approximately equal to the background luminance.

Michelson contrast

The Michelson contrast[4] is commonly used for patterns where both bright and dark features are equivalent and take up similar fractions of the area. The Michelson contrast is defined as

$$\frac{I_\mathrm{max} - I_\mathrm{min}}{I_\mathrm{max} + I_\mathrm{min}},$$

with I_max and I_min representing the highest and lowest luminance. The denominator represents twice the average of the luminance.

RMS contrast

Root mean square (RMS) contrast does not depend on the spatial frequency content or the spatial distribution of contrast in the image. RMS contrast is defined as the standard deviation of the pixel intensities:[5]

$$\sqrt{\frac{1}{MN}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}(I_{ij} - \bar{I})^2},$$

where intensities I_{ij} are the i -th j -th element of the two dimensional image of size M by N . $\bar{I}$ is the average intensity of all pixel values in the image. The image I is assumed to have its pixel intensities normalized in the range $[0, 1]$.

Contrast sensitivity

Contrast sensitivity is a measure of the ability to discern between luminances of different levels in a static image. Contrast sensitivity varies between individuals, reaching a maximum at approximately 20 years of age, and at spatial frequencies of about 2–5 cycles/degree. In addition it can decline with age and also due to other factors such as cataracts and diabetic retinopathy.[6]

In this image, the contrast amplitude depends only on the vertical coordinate, while the spatial frequency depends on the horizontal coordinate. Observe that for medium frequency you need less contrast than for high or low frequency to detect the sinusoidal fluctuation.

Improving contrast sensitivity

It was once thought that contrast sensitivity was relatively fixed and could only get worse with age. However new research has shown that playing videogames can slightly improve contrast sensitivity. [7]

See also

- Acutance
- Radiocontrast
- Contrast ratio

External links

- Details on luminance contrast [8]

References

[1] Campbell, FW and Robson, JG (1968). *Application of Fourier analysis to the visibility of gratings.* J. Physiol.

[2] "eye, human."Encyclopædia Britannica. 2008. Encyclopædia Britannica 2006 Ultimate Reference Suite DVD

[3] Travnikova, N. P. (1985). *Efficiency of Visual Search*. p.4. Mashinostroyeniye.

[4] Michelson, A. (1927). *Studies in Optics*. U. of Chicago Press.

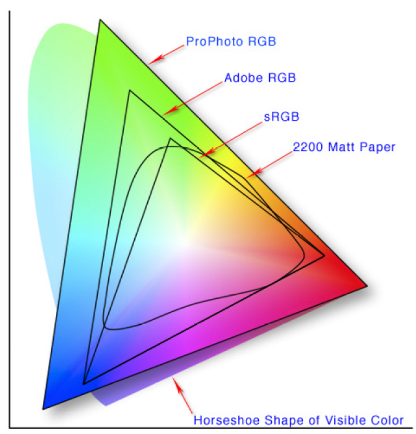
[5] E. Peli (Oct. 1990). "Contrast in Complex Images" (http://www.eri.harvard.edu/faculty/peli/papers/ContrastJOSA.pdf). *Journal of the Optical Society of America A* **7** (10): 2032–2040. doi:10.1364/JOSAA.7.002032. .

[6] Peter Wenderoth. "The Contrast Sensitivity Function" (http://vision.psy.mq.edu.au/~peterw/csf.html). .

[7] "Contrast sensitivity improvement" (http://www.clinical-ophthalmology.com/index.php?option=com_content&view=article&id=327:contrast-sensitivity-improved-by-video-games&catid=14:professional-news&Itemid=13). .

[8] http://colorusage.arc.nasa.gov/luminance_cont.php

Color space



A comparison of the chromaticities enclosed by some color spaces.

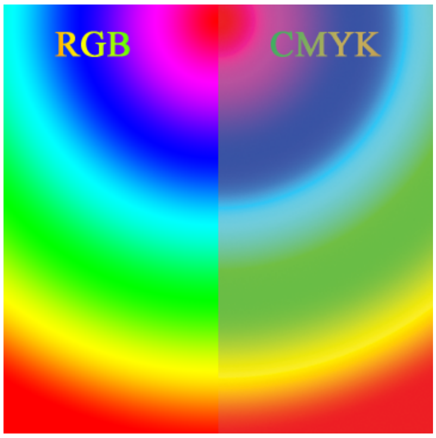
A color model is an abstract mathematical model describing the way colors can be represented as tuples of numbers, typically as three or four values or *color components* (e.g. RGB and CMYK are color models). However, a color model with no associated mapping function to an absolute color space is a more or less arbitrary color system with no connection to any globally-understood system of color interpretation.

Adding a certain mapping function between the color model and a certain reference color space results in a definite "footprint" within the reference color space. This "footprint" is known as a gamut, and, in combination with the color model, defines a new **color space**. For example, Adobe RGB and sRGB are two different absolute color spaces, both based on the RGB model.

In the most generic sense of the definition above, color spaces can be defined without the use of a color model. These spaces, such as Pantone, are in effect a given set of names or numbers which are defined by the existence of a corresponding set of physical color swatches. This article focuses on the mathematical model concept.

Understanding the concept

A wide range of colors can be created by the primary colors of pigment (cyan (C), magenta (M), yellow (Y), and black (K)). Those colors then define a specific color space. To create a three-dimensional representation of a color space, we can assign the amount of magenta color to the representation's X axis, the amount of cyan to its Y axis, and the amount of yellow to its Z axis. The resulting 3-D space provides a unique position for every possible color that can be created by combining those three pigments.



A comparison of RGB and CMYK color models. This image demonstrates the difference between how colors will look on a computer monitor (RGB) compared to how they will reproduce in a CMYK print process.

However, this is not the only possible color space. For instance, when colors are displayed on a computer monitor, they are usually defined in the RGB (red, green and blue) color space. This is another way of making nearly the same colors (limited by the reproduction medium, such as the phosphor (CRT) or filters and backlight (LCD)), and red, green and blue can be considered as the X, Y and Z axes. Another way of making the same colors is to use their Hue (X axis), their Saturation (Y axis), and their brightness Value (Z axis). This is called the HSV color space. Many color spaces can be represented as three-dimensional (X,Y,Z) values in this manner, but some have more, or fewer dimensions, and some cannot be represented in this way at all.

Notes

When formally defining a color space, the usual reference standard is the CIELAB or CIEXYZ color spaces, which were specifically designed to encompass all colors the average human can see.

Since "color space" is a more specific term for a certain *combination* of a color model plus a mapping function, the term "color space" tends to be used to also identify color models, since identifying a color space automatically identifies the associated color model. Informally, the two terms are often used interchangeably, though this is strictly incorrect. For example, although several specific color spaces are based on the RGB model, there is no such thing as *the* RGB color space.

Since any color space defines colors as a function of the absolute reference frame, color spaces, along with device profiling, allow reproducible representations of color, in both analogue and digital representations.

Conversion

Color space conversion is the translation of the representation of a color from one basis to another. This typically occurs in the context of converting an image that is represented in one color space to another color space, the goal being to make the translated image look as similar as possible to the original.

Density

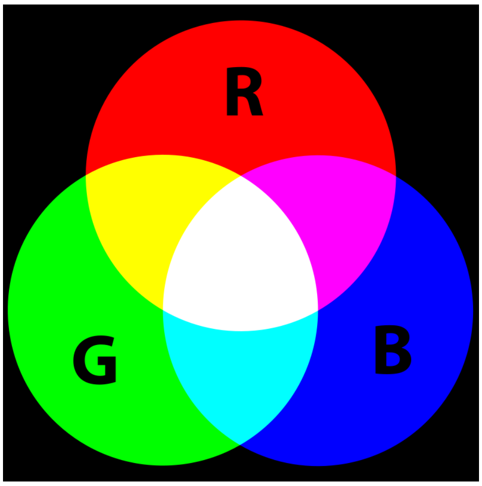
The RGB color model is implemented in different ways, depending on the capabilities of the system used. By far the most common general-used incarnation as of 2006 is the 24-bit implementation, with 8 bits, or 256 discrete levels of color per channel. Any color space based on such a 24-bit RGB model is thus limited to a range of 256×256×256 ≈ 16.7 million colors. Some implementations use 16 bits per component for 48 bits total, resulting in the same gamut with a larger number of distinct colors. This is especially important when working with wide-gamut color spaces (where most of the more common colors are located relatively close together), or when a large number of digital filtering algorithms are used consecutively. The same principle applies for any color space based on the same color model, but implemented in different bit depths.

Partial list of color spaces

CIE 1931 XYZ color space was one of the first attempts to produce a color space based on measurements of human color perception (earlier efforts were by James Clerk Maxwell, König & Dieterici, and Abney at Imperial College)[1] and it is the basis for almost all other color spaces. Derivatives of the CIE XYZ space include CIELUV, CIEUVW, and CIELAB.

Generic color models

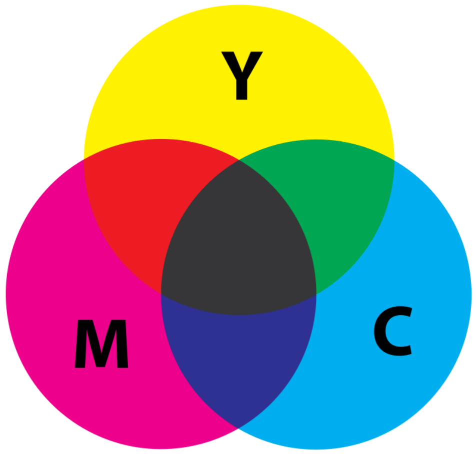
RGB uses additive color mixing, because it describes what kind of *light* needs to be *emitted* to produce a given color. Light is added together to create form from out of the darkness. RGB stores individual values for red, green and blue. RGBA is RGB with an additional channel, alpha, to indicate transparency.



Additive color mixing: Three overlapping lightbulbs in a vacuum, adding together to create white.

Common color spaces based on the RGB model include sRGB, Adobe RGB and ProPhoto RGB.

CMYK uses subtractive color mixing used in the printing process, because it describes what kind of inks need to be applied so the light *reflected* from the substrate and through the inks produces a given color. One starts with a white substrate (canvas, page, etc), and uses ink to subtract color from white to create an image. CMYK stores ink values for cyan, magenta, yellow and black. There are many CMYK color spaces for different sets of inks, substrates, and press characteristics (which change the dot gain or transfer function for each ink and thus change the appearance).



Subtractive color mixing: Three splotches of paint on white paper, subtracting together to turn the paper black.

YIQ was formerly used in NTSC (North America, Japan and elsewhere) television broadcasts for historical reasons. This system stores a luminance value with two chrominance values, corresponding approximately to the amounts of blue and red in the color. It is similar to the YUV scheme used in most video capture systems[2] and in PAL (Australia, Europe, except France, which uses SECAM) television, except that the YIQ color space is rotated 33° with respect to the YUV color space. The YDbDr scheme used by SECAM television is rotated in another way.

YPbPr is a scaled version of YUV. It is most commonly seen in its digital form, YCbCr, used widely in video and image compression schemes such as MPEG and JPEG.

xvYCC is a new international digital video color space standard published by the IEC (IEC 61966-2-4). It is based on the ITU BT.601 and BT.709 standards but extends the gamut beyond the R/G/B primaries specified in those standards.

HSV (**h**ue, **s**aturation, **v**alue), also known as HSB (hue, saturation, **b**rightness) is often used by artists because it is often more natural to think about a color in terms of hue and saturation than in terms of additive or subtractive color components. HSV is a transformation of an RGB colorspace, and its components and colorimetry are relative to the RGB colorspace from which it was derived.

HSL (**h**ue, **s**aturation, **l**ightness/**l**uminance), also known as HLS or HSI (hue, saturation, **i**ntensity) is quite similar to HSV, with "lightness" replacing "brightness". The difference is that the *brightness* of a pure color is equal to the brightness of white, while the *lightness* of a pure color is equal to the lightness of a medium gray.

Commercial color spaces

- Munsell color system
- Natural Color System (NCS)

Special-purpose color spaces

- The RG Chromaticity space is used in Computer vision applications. It shows the color of light (red, yellow, green etc.), but not its intensity (dark, bright).

Obsolete color spaces

Early color spaces had two components. They largely ignored blue light because the added complexity of a 3-component process provided only a marginal increase in fidelity when compared to the jump from monochrome to 2-component color.

- RG for early Technicolor film
- RGK for early color printing

See also

- Color theory
- List of colors

External links

- Color FAQ [5], Charles Poynton
- FAQ about color physics [3], Stephen Westland
- Color Science [4], Dan Bruton
- Color Spaces [5], Rolf G. Kuehni (October 2003)
- Colour spaces - perceptual, historical and applicational background [6], Marko Tkalčič (2003)
- Color formats [7] for image and video processing - Color conversion [8] between RGB, YUV, YCbCr and YPbPr.

References

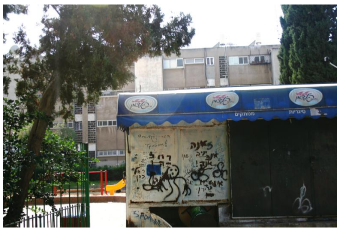
[1] William David Wright, *50 years of the 1931 CIE Standard Observer*. Die Farbe, **29**:4/6 (1981).
[2] Dean Anderson. "Color Spaces in Frame Grabbers: RGB vs. YUV" (http://www.sensoray.com/support/frame_grabber_capture_modes.htm). . Retrieved 2008-04-08.
[3] http://www.colourware.co.uk/cpfaq.htm
[4] http://www.physics.sfasu.edu/astro/color.html
[5] http://www4.ncsu.edu/~rgkuehni/PDFs/ColSp.pdf
[6] http://ldos.fe.uni-lj.si/docs/documents/20030929092037_markot.pdf
[7] http://www.equasys.de/colorformat.html
[8] http://www.equasys.de/colorconversion.html

Color mapping

Color mapping example

Source image

Reference image



Source image color mapped using histogram matching

Color mapping is a function that maps (transforms) the colors of one (source) image to the colors of another (target) image. A color mapping may be referred to as the algorithm that results in the mapping function or the algorithm that transforms the image colors. Color mapping is also sometimes called "color transfer".

Algorithms

There are two types of color mapping algorithms: Those that employ the statistics of the colors of two images, and those that rely on a given pixel correspondence between the images.

An example of an algorithm that employs the statistical properties of the images is histogram matching. This is a classic algorithm for color mapping, suffering from the problem of sensitivity to image content differences. Newer statistic-based algorithms deal with this problem. An example of such algorithm is adjusting the mean and the standard deviation of Lab channels of the two images.[1]

A common algorithm for computing the color mapping when the pixel correspondence is given is building the joint-histogram (see also co-occurrence matrix) of the two images and finding the mapping by using dynamic programming based on the joint-histogram values.[2]

When the pixel correspondence is not given and the image contents are different (due to different point of view), the statistics of the image corresponding regions can be used as an input to statistics-based algorithms, such as histogram matching. The corresponding regions can be found by detecting the corresponding features.[3]

Applications

Color mapping can serve two different purposes: One is calibrating the colors of two cameras for further processing using two or more sample images. The second is adjusting the colors of two images for perceptual visual compatibility.

Color calibration is an important pre-processing task in computer vision applications. Many applications simultaneously process two or more images and, therefore, need their colors to be calibrated. Examples of such applications are: Image differencing, registration, object recognition, multi-camera tracking, co-segmentation and stereo reconstruction.

References

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[3] Piecewise-consistent Color Mappings of Images Acquired Under Various Conditions (http://www.faculty.idc.ac.il/toky/Publications/Conference/colorMap.pdf)

Color management

In digital imaging systems, **color management** is the controlled conversion between the color representations of various devices, such as image scanners, digital cameras, monitors, TV screens, film printers, computer printers, offset presses, and corresponding media.

The primary goal of color management is to obtain a good match across color devices; for example, a video which should appear the same color on a computer LCD monitor, a plasma TV screen, and on a printed frame of video. Color management helps to achieve the same appearance on all of these devices, provided the devices are capable of delivering the needed color intensities.

Parts of this technology are implemented in the operating system (OS), helper libraries, the application, and devices. A cross-platform view of color management is the use of an ICC-compatible color management system. The International Color Consortium (ICC) is an industry consortium which has defined an open standard for a *Color Matching Module* (CMM) at the OS level, and color profiles for the devices and *working space* (color space the user edits in).

There are other approaches to color management besides using ICC profiles. This is partly due to history and partly because of other needs than the ICC standard covers. The film and broadcasting industries make use of many of the same concepts, but they more frequently rely on boutique solutions. The film industry, for instance, uses 3D LUTs (lookup table) to characterize color. At the consumer level, color management currently applies more to still images than video, in which color management is still in its infancy.[1]

Hardware

Characterization

In order to describe the behavior of the various output devices, they must be compared (measured) in relation to a standard color space. Often a step called linearization is performed first, in order to undo the effect of gamma correction that was done to get the most out of limited 8-bit color paths. Instruments used for measuring device colors include colorimeters and spectrophotometers. As an intermediate result, the device gamut is described in the form of scattered measurement data. The transformation of the scattered measurement data into a more regular form, usable by the application, is called *profiling*. Profiling is a complex process involving mathematics, intense computation, judgment, testing, and iteration. After the profiling is finished, an idealized color description of the device is created. This description is called a *profile*.

Calibration

Calibration is like characterization, except that it can include the adjustment of the device, as opposed to just the measurement of the device. Color management is sometimes sidestepped by calibrating devices to a common standard color space such as sRGB; when such calibration is done well enough, no color translations are needed to get all devices to handle colors consistently. This avoidance of the complexity of color management was one of the goals in the development of sRGB.

Color profiles

Embedding

Image formats themselves (such as TIFF, JPEG, PNG, EPS, PDF, and SVG) may contain embedded color profiles but are not required to do so by the image format. The International Color Consortium standard was created to bring various developers and manufacturers together. The ICC standard permits the exchange of output device characteristics and color spaces in the form of metadata. This allows the embedding of color profiles into images as well as storing them in a database or a profile directory.

Working spaces

Working spaces, such as sRGB, Adobe RGB or ProPhoto are color spaces that facilitate good results while editing. For instance, pixels with equal values of R,G,B should appear neutral. Using a large (gamut) working space will lead to posterization, while using a small working space will lead to clipping.[2] This trade-off is a consideration for the critical image editor.

Color translation

Color translation, or color space conversion, is the translation of the representation of a color from one color space to another. This calculation is required whenever data is exchanged inside a color-managed chain. Transforming profiled color information to different output devices is achieved by referencing the profile data into a standard color space. It is easy to convert colors from one device to a selected standard and from that color space to the colors of another device. By ensuring that the reference color space covers the many possible colors that humans can see, this concept allows one to exchange colors between many different color output devices.

Profile connection space

In the terminology of the International Color Consortium, a translation between two color spaces can go through a *profile connection space* (PCS): Color Space 1 → PCS (CIELAB or CIEXYZ) → Color space 2; conversions into and out of the PCS are each specified by a profile.[3]

Gamut mapping

Since different devices don't have the same gamut, they need some rearrangement near the borders of the gamut. Some colors need to be shifted to the inside of the gamut as they otherwise cannot be represented on the output device and would simply be clipped. For instance to print a mostly saturated blue from a monitor to paper with a typical CMYK printer will surely fail. The paper blue will not be that saturated. Conversely, the bright cyan of an inkjet printer cannot be easily presented on an average computer monitor. The color management system can utilize various methods to achieve desired results and give experienced users control of the gamut mapping behavior.

Rendering intent

When the gamut of source color space exceeds that of the destination, saturated colors are liable to become clipped (inaccurately represented). The color management module can deal with this problem in several ways. The ICC specification includes four different *rendering intents*: absolute colorimetric, relative colorimetric, perceptual, and saturation.[3]

Absolute colorimetric

Absolute colorimetry and relative colorimetry actually use the same table but differ in the adjustment for the white point media. If the output device has a much larger gamut than the source profile, i.e., all the colors in the source can be represented in the output, using the absolute colorimetry rendering intent would "ideally" (ignoring noise, precision, etc) give an exact output of the specified CIELAB values. Perceptually, the colors may appear incorrect, but instrument measurements of the resulting output would match the source. Colors outside of the proof print system's possible color are mapped to the boundary of the color gamut. Absolute colorimetry is useful to get an exact specified color (e.g., IBM blue), or to quantify the accuracy of mapping methods.

Relative colorimetric

The goal in relative colorimetry is to be truthful to the specified color, with only a correction for the media. Relative colorimetry is useful in proofing applications, since you are using it to get an idea of how a print on one device will appear on a different device. Media differences are the only thing you really would like to adjust for. Obviously there has to be some gamut mapping going on also. Usually this is done in a way where hue and lightness are maintained at the cost of reduced saturation. Relative colorimetric is the default rendering intent on most systems.

Perceptual and Saturation

The perceptual and saturation intents are where the results really depend upon the profile maker. This is even how some of the competitors in this market differentiate themselves. These intents should be created by the profile maker so that pleasing images occur with the perceptual intent while eye-catching business graphics occur with the saturation intent. This is achieved through the use of different perceptual remaps of the data as well as different gamut mapping methods. Perceptual rendering is recommended for color separation

Implementation

Color management module

Color matching module (also -method or -system) is a software algorithm that adjusts the numerical values that get sent to or received from different devices so that the perceived color they produce remains consistent. The key issue here is how to deal with a color that cannot be reproduced on a certain device in order to show it through a different device as if it were visually the same color, just as when the reproducible color range between color transparencies and printed matters are different. There is no common method for this process, and the performance depends on the capability of each color matching method.

Some well known CMMs are ColorSync, Adobe CMM [4], LittleCMS, and ArgyllCMS [5].

Operating system level

Beginning with Windows Vista, color management in Windows is handled at the OS level through an ICC color management standard and API known as Windows Color System.[6] WCS supplements the *Image Color Management* (ICM) system in Windows 2000 and Windows XP, originally written by Heidelberg.[7] [8]

Apple's Mac operating systems have provided OS-level color management since 1993, through ColorSync.

Operating systems which use the X Window System for graphics use ICC profiles, but support for color management on Linux is still quite nascent, with only a handful of applications supporting, some through LittleCMS.

Application level

Most web browsers ignore color profiles.[9] Notable exceptions are Safari, starting with version 2.0, and Firefox starting with version 3.0. Although disabled by default in Firefox 3.0, users can enable ICC v2 and ICC v4 color management by using an add-on[10] or setting the value "gfx.color_management.enabled" to "true" in Firefox 3's "about:config" file.[11] . Starting from Firefox 3.5 color management is enabled by default only for tagged images, although support is limited to ICC v2 profiles owing to a change in color management systems from 3.0[12] . FastPictureViewer, a commercial image viewer for Windows, features full color management support (monitor profile and image profiles).

See also

- Color chart
- International Color Consortium
- IT8

Further reading

- Fraser, Bruce; Bunting, Fred; Murphy, Chris (2004). *Real World Color Management*. Berkeley, CA, USA: Peachpit Press. ISBN 0-201-77340-6.
- Schwartz, Charles S. (2004). *Understanding Digital Cinema: A Professional Handbook*. Focal Press. ISBN 978-0240806174.
- Morovic, Jan (2008). *Color Gamut Mapping*. Wiley. ISBN 978-0470030325.

External links

- Color management and color science: Introduction [13] by Norman Koren.
- ColorWiki [14] by Steve Upton.

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[4] http://www.adobe.com/support/downloads/detail.jsp?ftpID=3618

[5] http://www.argyllcms.com/

[6] Upton, Steve (February 2008). Vista's New Color Management System: WCS (http://www.colorwiki.com/wiki/Vista's_New_Color_Management_System_-_WCS).

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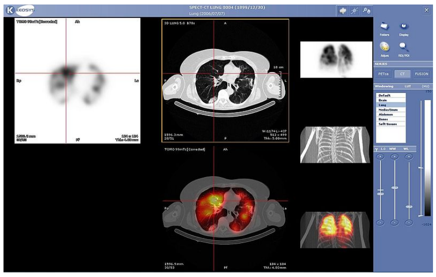
[8] The reader may verify this by examining the *Properties* of any ICM profile. The *Profile Information* tab should contain the entry "LinoColorCMM © by Heidelberger Druckmaschinen AG".

[9] Smith, Colin; Kabili, Jan (2005). *How to Wow: Photoshop CS2 for the Web* (http://books.google.com/books?id=I1H0fNcAPHcC&pg=PT17&dq=web+browsers+ignore+"icc+profiles"&ei=FXsjSIKHBae-ygSmmJjGDQ&client=firefox-a&sig=xr_yp7U_lzTv6M3KeChpRgAkTX8). Berkeley, CA: Peachpit Press. pp. 13. ISBN 0-321-39394-5. . Retrieved 2008-05-08. "Many designers choose not to include ICC Profiles with Web files because most Web browsers can't read them and they increase the size of a file."
[10] Color Management add-on (https://addons.mozilla.org/en-US/firefox/addon/6891) by Sean Hayes.
[11] Firefox 3: Color profile support (oh the pretty, pretty colors) (http://www.dria.org/wordpress/archives/2008/04/29/633/), Deb Richardson, Mozilla Corporation.
[12] (https://bugzilla.mozilla.org/show_bug.cgi?id=463221)
[13] http://www.normankoren.com/color_management.html
[14] http://www.colorwiki.com

Digital Imaging and Communications in Medicine

Digital **I**maging and **Co**mmunications in **M**edicine (**DICOM**) is a standard for handling, storing, printing, and transmitting information in medical imaging. It includes a file format definition and a network communications protocol. The communication protocol is an application protocol that uses TCP/IP to communicate between systems. DICOM files can be exchanged between two entities that are capable of receiving image and patient data in DICOM format. The National Electrical Manufacturers Association (NEMA) holds the copyright to this standard.[1] It was developed by the *DICOM Standards Committee*, whose members[2] are also partly members of NEMA.[3]



A nuclear medicine image in DICOM format

DICOM enables the integration of scanners, servers, workstations, printers, and network hardware from multiple manufacturers into a picture archiving and communication system (PACS). The different devices come with DICOM conformance statements which clearly state the DICOM classes they support. DICOM has been widely adopted by hospitals and is making inroads in smaller applications like dentists' and doctors' offices.

DICOM is known as NEMA Standard PS3, and as ISO Standard 12052.

Parts of the DICOM Standard

The DICOM standard is divided into related but independent parts:[4]

The links below are to the 2009 version published in January 2010. Additions to the standard (Supplements and Change Proposals) since that publication are available through the DICOM Web site [5].

- PS 3.1: Introduction and Overview [6]PDF (241 KB)
- PS 3.2: Conformance [7]PDF (6.46 MB)
- PS 3.3: Information Object Definitions [8]PDF (6.96 MB)
- PS 3.4: Service Class Specifications [9]PDF (1.07 MB)
- PS 3.5: Data Structure and Encoding [10]PDF (1.43 MB)
- PS 3.6: Data Dictionary [11]PDF (7.32 MB)
- PS 3.7: Message Exchange [12]PDF (1.97 MB)
- PS 3.8: Network Communication Support for Message Exchange [13]PDF (901 KB)
- PS 3.9: Retired (formerly Point-to-Point Communication Support for Message Exchange)
- PS 3.10: Media Storage and File Format for Data Interchange [14]PDF (406 KB)
- PS 3.11: Media Storage Application Profiles [15]PDF (1.14 MB)
- PS 3.12: Storage Functions and Media Formats for Data Interchange [16]PDF (593 KB)

- PS 3.13: Retired (formerly Print Management Point-to-Point Communication Support)
- PS 3.14: Grayscale Standard Display Function [17]PDF (2.88 MB)
- PS 3.15: Security and System Management Profiles [18]PDF (1.00 MB)
- PS 3.16: Content Mapping Resource [19]PDF (3.08 MB)
- PS 3.17: Explanatory Information [20]PDF (3.28 MB)
- PS 3.18: Web Access to DICOM Persistent Objects (WADO) [21]PDF (291 KB)

History

DICOM is the third version of a standard developed by American College of Radiology (ACR) and National Electrical Manufacturers Association (NEMA).

In the beginning of the 1980s it was almost impossible for anyone other than manufacturers of computed tomography or magnetic resonance imaging devices to decode the images that the machines generated. Radiologists wanted to use the images for dose-planning for radiation therapy. ACR and NEMA joined forces and formed a standard committee in 1983. Their first standard, ACR/NEMA 300, was released in 1985. Very soon after its release, it became clear that improvements were needed. The text was vague and had internal contradictions.

Front page of ACR/NEMA 300, version 1.0, which was released in 1985

In 1988 the second version was released. This version gained more acceptance among vendors. The image transmission was specified as over a dedicated 25 differential (EIA-485) pair cable. The first demonstration of ACR/NEMA V2.0 interconnectivity technology was held at Georgetown University, May 21-23, 1990. Six companies participated in this event, DeJarnette Research Systems, General Electric Medical Systems, Merge Technologies, Siemens Medical Systems, Vortech (acquired by Kodak that same year) and 3M. Commercial equipment supporting ACR/NEMA 2.0 was presented at the annual meeting of the Radiological Society of North America (RSNA) in 1990 by these same vendors. Many soon realized that the second version also needed improvement. Several extensions to ACR/NEMA 2.0 were created, like Papyrus (developed by the University Hospital of Geneva, Switzerland) and SPI, (Standard Product Interconnect, driven by Siemens Medical Systems and Philips Medical Systems).

The first large scale deployment of ACR/NEMA technology was made in 1992 by the US Army and Air Force as part of the MDIS (Medical Diagnostic Imaging Support) [22] program run out of Ft. Detrick, Maryland. Loral Aerospace and Siemens Medical Systems led a consortium of companies in deploying the first US military PACS (Picture Archiving and Communications System) at all major Army and Air Force medical treatment facilities and teleradiology nodes at a large number of US military clinics. DeJarnette Research Systems and Merge Technologies provided the modality gateway interfaces from third party imaging modalities to the Siemens SPI network. The Veterans Administration and the Navy also purchased systems off this contract.

In 1993 the third version of the standard was released. Its name was then changed to DICOM so as to improve the possibility of international acceptance as a standard. New service classes were defined, network support added and the Conformance Statement was introduced. Officially, the latest version of the standard is still 3.0, however, it has been constantly updated and extended since 1993. Instead of using the version number the standard is often version-numbered using the release year, like "the 2007 version of DICOM".

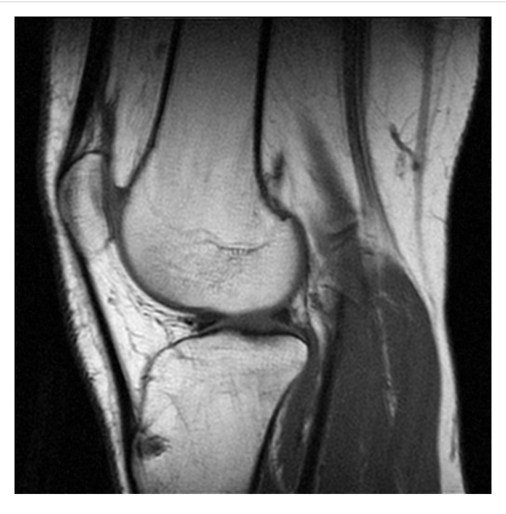
While the DICOM standard has achieved a near universal level of acceptance amongst medical imaging equipment vendors and healthcare IT organizations, the standard has its limitations. DICOM is a standard directed at addressing technical interoperability issues in medical imaging. It is not a framework or architecture for achieving a useful clinical workflow. RSNA's Integrating the Healthcare Enterprise (IHE) initiative layered on top of DICOM (and HL-7) provides this final piece of the medical imaging interoperability puzzle.

Derivations

There are some derivations from the DICOM standard into other application areas. This includes

- **DICONDE** - *Digital Imaging and Communication in Nondestructive Evaluation*, was established in 2004 as a way for nondestructive testing manufacturers and users to share image data.[23]
- **DICOS** - *Digital Imaging and Communication in Security* was established in 2009 to be used for image sharing in airport security.[24]

DICOM Data Format



DICOM differs from other data formats in that it groups information into data sets. That means that a file of a chest X-Ray image, for example, actually contains the patient ID within the file, so that the image can never be separated from this information by mistake.

A DICOM data object consists of a number of attributes, including items such as name, ID, etc., and also one special attribute containing the image pixel data (i.e. logically, the main object has no "header" as such - merely a list of attributes, including the pixel data). A single DICOM object can only contain one attribute containing pixel data. For many modalities, this corresponds to a single image. But note that the attribute may contain multiple "frames", allowing storage of cine loops or other multi-frame data. Another example is NM data, where an NM image by definition is a multi-dimensional multi-frame image. In these cases three- or four-dimensional data can be encapsulated in a single DICOM object. Pixel data can be compressed using a variety of standards, including JPEG, JPEG Lossless, JPEG 2000, and Run-length encoding (RLE). LZW (zip) compression can be used for the whole data set (not just the pixel data) but this is rarely implemented.

DICOM uses three different Data Element encoding schemes. With Explicit Value Representation (VR) Data Elements, for VRs that are not OB, OW, OF, SQ, UT, or UN, the format for each Data Element is: GROUP (2 bytes) ELEMENT (2 bytes) VR (2 bytes) LengthInByte (2 bytes) Data (variable length). For the other Explicit Data Elements or Implicit Data Elements, see section 7.1 of Part 5 of the DICOM Standard.

The same basic format is used for all applications, including network and file usage, but when written to a file, usually a true "header" (containing copies of a few key attributes and details of the application which wrote it) is added.

DICOM Value Representations

Extracted from Chapter 6.2 of

- PS 3.5: Data Structure and Encoding [25]PDF (1.43 MiB)

Value Representation	Description
AE	Application Entity
AS	Age String
AT	Attribute Tag
CS	Code String
DA	Date
DS	Decimal String
DT	Date/Time
FL	Floating Point Single (4 bytes)
FD	Floating Point Double (8 bytes)
IS	Integer String
LO	Long String
LT	Long Text
OB	Other Byte
OF	Other Float
OW	Other Word
PN	Person Name
SH	Short String
SL	Signed Long
SQ	Sequence of Items
SS	Signed Short
ST	Short Text
TM	Time
UI	Unique Identifier
UL	Unsigned Long
UN	Unknown
US	Unsigned Short
UT	Unlimited Text

In addition to a Value Representation, each attribute also has a Value Multiplicity to indicate the number of data elements contained in the attribute. For character string value representations, if more than one data element is being encoded, the successive data elements are separated by the backslash character "\".

DICOM Services

DICOM consists of **many** different services, most of which involve transmission of data over a network, and the file format below is a later and relatively minor addition to the standard.

Store

The **DICOM** Store service is used to send images or other persistent objects (structured reports, etc.) to a PACS or workstation.

Storage Commitment

The DICOM storage commitment service is used to confirm that an image has been permanently stored by a device (either on redundant disks or on backup media, e.g. burnt to a CD). The Service Class User (SCU - similar to a client), a modality or workstation, etc., uses the confirmation from the Service Class Provider (SCP - similar to a server), an archive station for instance, to make sure that it is safe to delete the images locally.

Query/Retrieve

This enables a workstation to find lists of images or other such objects and then retrieve them from a PACS.

Modality Worklist

This enables a piece of imaging equipment (a modality) to obtain details of patients and scheduled examinations electronically, avoiding the need to type such information multiple times (and the mistakes caused by retyping).

Modality Performed Procedure Step

A complementary service to Modality Worklist, this enables the modality to send a report about a performed examination including data about the images acquired, beginning time, end time, and duration of a study, dose delivered, etc. It helps give the radiology department a more precise handle on resource (acquisition station) use. Also known as MPPS, this service allows a modality to better coordinate with image storage servers by giving the server a list of objects to send before or while actually sending such objects.

Printing

The DICOM Printing service is used to send images to a DICOM Printer, normally to print an "X-Ray" film. There is a standard calibration (defined in DICOM Part 14) to help ensure consistency between various display devices, including hard copy printout.

Off-line Media (DICOM Files)

The off-line media files correspond to Part 10 of the DICOM standard. It describes how to store medical imaging information on removable media. Except for the data set containing, for example, an image and demography, it's also mandatory to include the File Meta Information.

DICOM restricts the filenames on DICOM media to 8 characters (some systems wrongly use 8.3, but this is not legal). No information must be extracted from these names (PS3.10 Section 6.2.3.2). This is a common source of problems with media created by developers who did not read the specifications carefully. This is a historical requirement to maintain compatibility with older existing systems. It also mandates the presence of a media directory, the DICOMDIR file, which provides index and summary information for all the DICOM files on the media. The DICOMDIR information provides substantially greater information about each file than any filename could, so there is less need for meaningful file names.

DICOM files typically have a .dcm file extension.

The MIME type for DICOM files is defined by RFC 3240 as application/dicom.

There is also an ongoing media exchange test and "connectathon" process for CD media and network operation that is organized by the IHE organization.

Application areas

Modality	Description
BI	Modality of type Biomagnetic Imaging
CD	Modality of type Color Flow Doppler-Retired 2008
CR	Modality of type Computed Radiography
CT	Modality of type Computed Tomography
DD	Modality of type Duplex Doppler-Retired 2008
DG	Modality of type Diaphanography
DX	Modality of type Digital Radiography
EC	Modality of type Echo cardiography - Retired
EM	Modality of type Electron Microscope
ES	Modality of type Endoscopy
GM	Modality of type General Microscopy
LS	Modality of type Laser Surface Scan
MA	Modality of type Magnetic Resonance Angiography - Retired
MG	Modality of type Mammography
MR	Modality of type Magnetic Resonance
MS	Modality of type Magnetic Resonance Spectroscopy - Retired
NM	Modality of type Nuclear Medicine
OT	Modality of type Other
PT	Modality of type Positron Emission Tomography
RF	Modality of type Radio Fluoroscopy
RG	Modality of type Radiographic Imaging (conventional film screen)
RT	Modality of type Radiation Therapy
SC	Modality of type Secondary Capture
SM	Modality of type Slide Microscopy
ST	Modality of type Single-Photon Emission Computed Tomography - Retired 2008
TG	Modality of type Thermography
US	Modality of type Ultra Sound
VL	Modality of type Visible Light
XA	Modality of type X-Ray Angiography
XC	Modality of type External Camera (Photography)

Examples of Modalities supported in DICOM are:

- AS = Angioscopy-Retired
- BI = Biomagnetic Imaging

- CD = Color Flow Doppler-Retired
- CF = Cinefluorography (retired)
- CP = Colposcopy Retired
- CR = Computed Radiography
- CS = CystoscopyRetired
- CT = Computed Tomography
- DD = Duplex Doppler Retired
- DF = Digital Fluoroscopy (retired)
- DG = Diaphanography
- DM = Digital Microscopy
- DS = Digital Subtraction Angiography Retired
- DX = Digital radiography
- EC = Echocardiography Retired
- ES = Endoscopy
- FA = Fluorescein Angiography Retired
- FS = Fundoscopy Retired
- HC = Hard Copy
- LP = Laparoscopy Retired
- LS = Laser Surface Scan
- MA = Magnetic resonance angiography Retired
- MG = Mammography
- MR = Magnetic Resonance
- MS = Magnetic Resonance Spectroscopy Retired
- NM = Nuclear Medicine
- OT = Other
- PT = Positron Emission Tomography (PET)
- RF = Radio Fluoroscopy
- RG = Radiographic Imaging (conventional film screen)
- RTDOSE (a.k.a. RD) = Radiotherapy Dose
- RTIMAGE = Radiotherapy Image
- RTPLAN (a.k.a. RP) = Radiotherapy Plan
- RTSTRUCT (a.k.a. RS) = Radiotherapy Structure Set
- SR = Structured Reporting
- ST = Single-photon Emission Computed Tomography Retired
- TG = Thermography
- US = Ultrasound
- VF = Videofluorography (retired)
- XA = X-Ray Angiography
- XC = eXternal Camera
- ECG = Electrocardiograms

DICOM port numbers

DICOM have reserved the following TCP and UDP port numbers by the Internet Assigned Numbers Authority (IANA):

- **104** well-known port for DICOM over TCP or UDP. Since 104 is in the reserved subset, many operating systems require special privileges to use it.
- **2761** registered port for DICOM using Integrated Secure Communication Layer (ISCL) over TCP or UDP
- **2762** registered port for DICOM using Transport Layer Security (TLS) over TCP or UDP
- **11112** registered port for DICOM using standard, open communication over TCP or UDP

The standard recommends but does not require the use of these port numbers.

External links

- The latest DICOM specification [26]
- DICOM Standard Status (approved and proposed changes) [27]
- Brief introduction to DICOM [28]
- Introduction to DICOM using OsiriX [29]
- Medical Image FAQ part 2 [30] - Standard formats including DICOM.
- Medical Image FAQ part 8 [31] - Contains a long list DICOM software.
- Collection of DICOM images (clinical images and technical testpatterns) [32]

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[12] ftp://medical.nema.org/medical/dicom/2009/09_07pu2.pdf
[13] ftp://medical.nema.org/medical/dicom/2009/09_08pu.pdf
[14] ftp://medical.nema.org/medical/dicom/2009/09_10pu.pdf
[15] ftp://medical.nema.org/medical/dicom/2009/09_11pu.pdf
[16] ftp://medical.nema.org/medical/dicom/2009/09_12pu.pdf
[17] ftp://medical.nema.org/medical/dicom/2009/09_14pu.pdf
[18] ftp://medical.nema.org/medical/dicom/2009/09_15pu.pdf
[19] ftp://medical.nema.org/medical/dicom/2009/09_16pu.pdf
[20] ftp://medical.nema.org/medical/dicom/2009/09_17pu.pdf
[21] ftp://medical.nema.org/medical/dicom/2009/09_18pu.pdf
[22] http://www.ncbi.nlm.nih.gov/pubmed/7612705?dopt=Abstract
[23] http://www.astm.org: If a Picture Is Worth 1,000 Words, then Pervasive, Ubiquitous Imaging Is Priceless (http://www.astm.org/SNEWS/OCTOBER_2003/voelker_oct03.html)
[24] http://www.nema.org: Industrial Imaging and Communications Section (http://www.nema.org/prod/security/indust-Img.cfm)
[25] http://medical.nema.org/dicom/2007/07_05pu.pdf
[26] ftp://medical.nema.org/medical/dicom/2009/
[27] http://www.dclunie.com/dicom-status/status.html
[28] http://www.cabiatl.com/mricro/dicom/index.html
[29] http://www.saravanansubramanian.com/Saravanan/Articles_On_Software/Entries/2010/2/10_Introduction_to_the_DICOM_Standard.html

[30] http://www.dclunie.com/medical-image-faq/html/part2.html
[31] http://www.dclunie.com/medical-image-faq/html/part8.html
[32] http://www.aycan.de/main/lp/sample_dicom_images.html

JPEG 2000

Comparison of JPEG 2000 with the original JPEG format.

Filename extension	`.jp2`, `.j2k`, `.jpf`, `.jpx`, `.jpm`, `.mj2`
Internet media type	`image/jp2`, `image/jpx`, `image/jpm`, `video/mj2`
Uniform Type Identifier	`public.jpeg-2000`
Developed by	Joint Photographic Experts Group
Type of format	graphics file format
Standard(s)	ISO/IEC 15444

JPEG 2000 is a wavelet-based image compression standard and coding system. It was created by the Joint Photographic Experts Group committee in 2000 with the intention of superseding their original discrete cosine transform-based JPEG standard (created in 1992). The standardized filename extension is **.jp2** for ISO/IEC 15444-1 conforming files and **.jpx** for the extended part-2 specifications, published as ISO/IEC 15444-2. The registered MIME types are defined in RFC 3745. For ISO/IEC 15444-1 it is **image/jp2**.

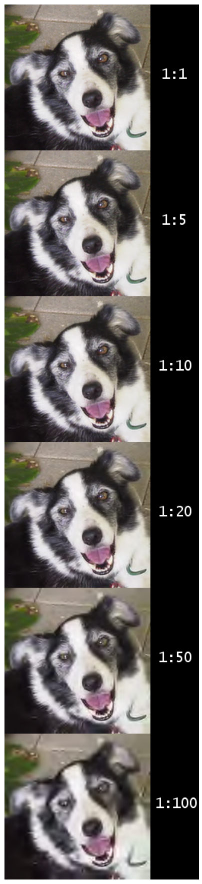
While there is a modest increase in compression performance of JPEG 2000 compared to JPEG, the main advantage offered by JPEG 2000 is the significant flexibility of the codestream. The codestream obtained after compression of an image with JPEG 2000 is scalable in nature, meaning that it can be decoded in a number of ways; for instance, by truncating the codestream at any point, one may obtain a representation of the image at a lower resolution, or signal-to-noise ratio. By ordering the codestream in various ways, applications can achieve significant performance increases. However, as a consequence of this flexibility, JPEG 2000 requires encoders/decoders that are complex and computationally demanding. Another difference, in comparison with JPEG, is in terms of visual artifacts: JPEG 2000 produces ringing artifacts, manifested as blur and rings near edges in the image, while JPEG produces ringing artifacts and 'blocking' artifacts, due to its 8×8 blocks.

JPEG 2000 has been published as an ISO standard, ISO/IEC 15444. As of 2010, JPEG 2000 is not widely supported in web browsers, and hence is not generally used on the World Wide Web.

Features

- *Superior compression performance*: at high bit rates, where artifacts become nearly imperceptible, JPEG 2000 has a small machine-measured fidelity advantage over JPEG. At lower bit rates (e.g., less than 0.25 bits/pixel for gray-scale images), JPEG 2000 has a much more significant advantage over certain modes of JPEG: artifacts are less visible and there is almost no blocking. The compression gains over JPEG are attributed to the use of DWT and a more sophisticated entropy encoding scheme.
- *Multiple resolution representation*: JPEG 2000 decomposes the image into a multiple resolution representation in the course of its compression process. This representation can be put to use for other image presentation purposes beyond compression as such.
- *Progressive transmission* by pixel and resolution accuracy, commonly referred to as progressive decoding and signal-to-noise ratio (SNR) scalability: JPEG 2000 provides efficient code-stream organizations which are progressive by pixel accuracy and by image resolution (or by image size). This way, after a smaller part of the whole file has been received, the viewer can see a lower quality version of the final picture. The quality then improves progressively through downloading more data bits from the source. The 1992 JPEG standard also has a progressive transmission feature but it's rarely used.
- *Lossless and lossy compression*: Like JPEG 1992,[1] the JPEG 2000 standard provides both lossless and lossy compression in a single compression architecture. Lossless compression is provided by the use of a reversible integer wavelet transform in JPEG 2000.
- *Random code-stream access and processing*, also referred as Region Of Interest (ROI): JPEG 2000 code streams offer several mechanisms to support spatial random access or region of interest access at varying degrees of granularity. This way it is possible to store different parts of the same picture using different quality.
- *Error resilience*: Like JPEG 1992, JPEG 2000 is robust to bit errors introduced by noisy communication channels, due to the coding of data in relatively small independent blocks.
- *Flexible file format*: The JP2 and JPX file formats allow for handling of color-space information, metadata, and for interactivity in networked applications as developed in the JPEG Part 9 JPIP protocol.
- *Side channel spatial information*: it fully supports transparency and alpha planes.

More advantages associated with JPEG 2000 can be referred to from the Official JPEG 2000 page [2].



Top-to-bottom demonstration of the artifacts of JPEG 2000 compression. The numbers indicate the compression ratio used. See the unscaled image for an accurate view.

JPEG 2000 image coding system - Parts

The JPEG 2000 image coding system (ISO/IEC 15444) consists of following parts:

JPEG 2000 image coding system - Parts[3] [4]

Part	Number	First public release date (First edition)	Latest public release date (edition)	Latest amendment	Identical ITU-T standard	Title	Description
Part 1	ISO/IEC 15444-1 [5]	2000	2004	2006[6]	T.800 [7]	Core coding system	the basic characteristics of JPEG 2000 compression (*.jp2*)
Part 2	ISO/IEC 15444-2 [8]	2004	2004	2006[9]	T.801 [10]	Extensions	(*.jpx*, *.jpf*)
Part 3	ISO/IEC 15444-3 [11]	2002	2007[12]		T.802 [13]	Motion JPEG 2000	(*.mj2*)
Part 4	ISO/IEC 15444-4 [14]	2002	2004[15]		T.803 [16]	Conformance testing	
Part 5	ISO/IEC 15444-5 [17]	2003	2003	2003[18]	T.804 [19]	Reference software	Java and C implementations
Part 6	ISO/IEC 15444-6 [20]	2003	2003	2007[21]		Compound image file format	(*.jpm*) e.g. document imaging, for pre-press and fax-like applications
Part 7	abandoned[3]					Guideline of minimum support function of ISO/IEC 15444-1[22]	(Technical Report on Minimum Support Functions[23])
Part 8	ISO/IEC 15444-8 [24]	2007	2007	2008[25]	T.807 [26]	Secure JPEG 2000	JPSEC (security aspects)
Part 9	ISO/IEC 15444-9 [27]	2005	2005	2008[28]	T.808 [29]	Interactivity tools, APIs and protocols	JPIP (interactive protocols and API)
Part 10	ISO/IEC 15444-10 [30]	2008	2008	2008[31]	T.809 [32]	Extensions for three-dimensional data	JP3D (volumetric imaging)
Part 11	ISO/IEC 15444-11 [33]	2007	2007[34]		T.810 [35]	Wireless	JPWL (wireless applications)
Part 12	ISO/IEC 15444-12 [36]	2004	2008[37]			ISO base media file format	
Part 13	ISO/IEC 15444-13 [38]	2008	2008[39]		T.812 [40]	An entry level JPEG 2000 encoder	
Part 14	under development[41] [42]					XML structural representation and reference	JPXML[43]

Technical discussion

The aim of JPEG 2000 is not only improving compression performance over JPEG but also adding (or improving) features such as scalability and editability. In fact, JPEG 2000's improvement in compression performance relative to the original JPEG standard is actually rather modest and should not ordinarily be the primary consideration for evaluating the design. Very low and very high compression rates are supported in JPEG 2000. In fact, the graceful ability of the design to handle a very large range of effective bit rates is one of the strengths of JPEG 2000. For example, to reduce the number of bits for a picture below a certain amount, the advisable thing to do with the first JPEG standard is to reduce the resolution of the input image before encoding it. That's unnecessary when using JPEG 2000, because JPEG 2000 already does this automatically through its multiresolution decomposition structure. The following sections describe the algorithm of JPEG 2000.

Color components transformation

Initially, images have to be transformed from the RGB color space to another color space, leading to three *components* that are handled separately. There are two possible choices:

1. Irreversible Color Transform (ICT) uses the well known YC_BC_R color space. It is called "irreversible" because it has to be implemented in floating or fix-point and causes round-off errors.
2. Reversible Color Transform (RCT) uses a modified YUV color space that does not introduce quantization errors, so it is fully reversible. Proper implementation of the RCT requires that numbers are rounded as specified that cannot be expressed exactly in matrix form. The transformation is:

$$Y_r = \left\lfloor \frac{R + 2G + B}{4} \right\rfloor ; C_b = B - G; C_r = R - G;$$

and $G = Y - \left\lfloor \frac{C_b + C_r}{4} \right\rfloor ; R = C_r + G; B = C_b + G.$

The chrominance components can be, but do not necessarily have to be, down-scaled in resolution; in fact, since the wavelet transformation already separates images into scales, downsampling is more effectively handled by dropping the finest wavelet scale. This step is called *multiple component transformation* in the JPEG 2000 language since its usage is not restricted to the RGB color model.

Tiling

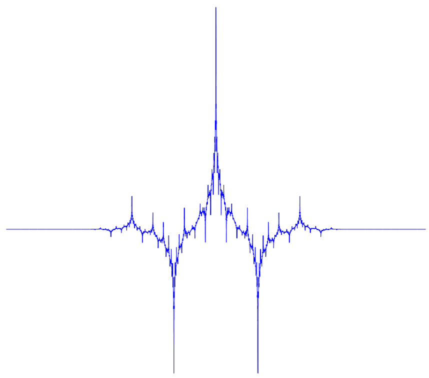
After color transformation, the image is split into so-called *tiles*, rectangular regions of the image that are transformed and encoded separately. Tiles can be any size, and it is also possible to consider the whole image as one single tile. Once the size is chosen, all the tiles will have the same size (except optionally those on the right and bottom borders). Dividing the image into tiles is advantageous in that the decoder will need less memory to decode the image and it can opt to decode only selected tiles to achieve a partial decoding of the image. The disadvantage of this approach is that the quality of the picture decreases due to a lower peak signal-to-noise ratio. Using many tiles can create a blocking effect similar to the older JPEG 1992 standard.

Wavelet transform

These tiles are then wavelet transformed to an arbitrary depth, in contrast to JPEG 1992 which uses an 8×8 block-size discrete cosine transform. JPEG 2000 uses two different wavelet transforms:

1. *irreversible*: the CDF 9/7 wavelet transform. It is said to be "irreversible" because it introduces quantization noise that depends on the precision of the decoder.
2. *reversible*: a rounded version of the biorthogonal CDF 5/3 wavelet transform. It uses only integer coefficients, so the output does not require rounding (quantization) and so it does not introduce any quantization noise. It is used in lossless coding.

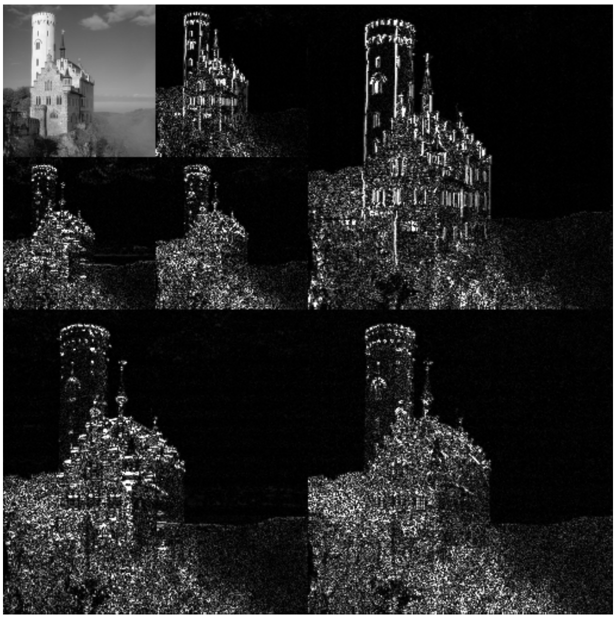
The wavelet transforms are implemented by the lifting scheme or by convolution.



CDF 5/3 wavelet used for lossless compression.

Quantization

After the wavelet transform, the coefficients are scalar-quantized to reduce the amount of bits to represent them, at the expense of a loss of quality. The output is a set of integer numbers which have to be encoded bit-by-bit. The parameter that can be changed to set the final quality is the quantization step: the greater the step, the greater is the compression and the loss of quality. With a quantization step that equals 1, no quantization is performed (it is used in lossless compression).



An example of the wavelet transform that is used in JPEG 2000. This is a 2nd-level CDF 9/7 wavelet transform.

Coding

The result of the previous process is a collection of *sub-bands* which represent several approximation scales. A sub-band is a set of *coefficients* — real numbers which represent aspects of the image associated with a certain frequency range as well as a spatial area of the image.

The quantized sub-bands are split further into *precincts*, rectangular regions in the wavelet domain. They are typically selected in a way that the coefficients within them across the sub-bands form approximately spatial blocks in the (reconstructed) image domain, though this is not a requirement.

Precincts are split further into *code blocks*. Code blocks are located in a single sub-band and have equal sizes — except those located at the edges of the image. The encoder has to encode the bits of all quantized coefficients of a code block, starting with the most significant bits and progressing to less significant bits by a process called the *EBCOT* scheme. *EBCOT* here stands for *Embedded Block Coding with Optimal Truncation*. In this encoding process, each bit plane of the code block gets encoded in three so-called *coding passes*, first encoding bits (and signs) of insignificant coefficients with significant neighbors (i.e., with 1-bits in higher bit planes), then refinement bits of significant coefficients and finally coefficients without significant neighbors. The three passes are called

Significance Propagation, *Magnitude Refinement* and *Cleanup* pass, respectively.

Clearly, in lossless mode all bit planes have to be encoded by the EBCOT, and no bit planes can be dropped.

The bits selected by these coding passes then get encoded by a context-driven binary arithmetic coder, namely the binary MQ-coder. The context of a coefficient is formed by the state of its nine neighbors in the code block.

The result is a bit-stream that is split into *packets* where a *packet* groups selected passes of all code blocks from a precinct into one indivisible unit. Packets are the key to quality scalability (i.e., packets containing less significant bits can be discarded to achieve lower bit rates and higher distortion).

Packets from all sub-bands are then collected in so-called *layers*. The way the packets are built up from the code-block coding passes, and thus which packets a layer will contain, is not defined by the JPEG 2000 standard, but in general a codec will try to build layers in such a way that the image quality will increase monotonically with each layer, and the image distortion will shrink from layer to layer. Thus, layers define the progression by image quality within the code stream.

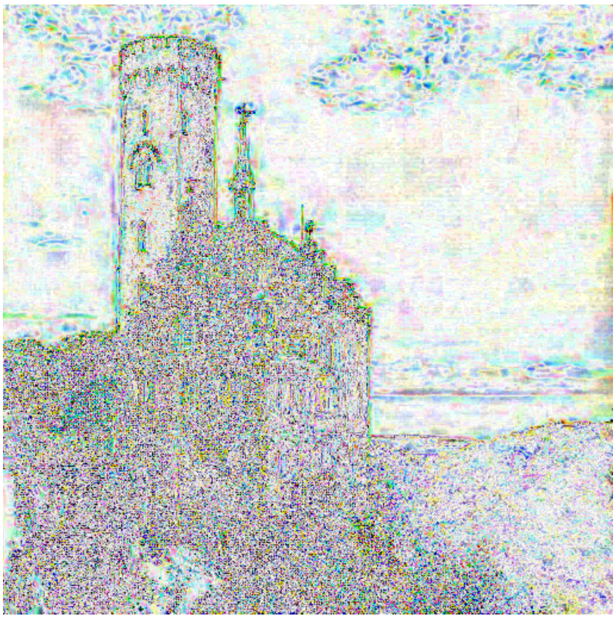
The problem is now to find the optimal packet length for all code blocks which minimizes the overall distortion in a way that the generated target bitrate equals the demanded bit rate.

While the standard does not define a procedure as to how to perform this form of rate–distortion optimization, the general outline is given in one of its many appendices: For each bit encoded by the EBCOT coder, the improvement in image quality, defined as mean square error, gets measured; this can be implemented by an easy table-lookup algorithm. Furthermore, the length of the resulting code stream gets measured. This forms for each code block a graph in the rate–distortion plane, giving image quality over bitstream length. The optimal selection for the truncation points, thus for the packet-build-up points is then given by defining critical *slopes* of these curves, and picking all those coding passes whose curve in the rate–distortion graph is steeper than the given critical slope. This method can be seen as a special application of the method of *Lagrange multiplier* which is used for optimization problems under constraints. The Lagrange multiplier, typically denoted by ?, turns out to be the critical slope, the constraint is the demanded target bitrate, and the value to optimize is the overall distortion.

Packets can be reordered almost arbitrarily in the JPEG 2000 bit-stream; this gives the encoder as well as image servers a high degree of freedom.

Already encoded images can be sent over networks with arbitrary bit rates by using a layer-progressive encoding order. On the other hand, color components can be moved back in the bit-stream; lower resolutions (corresponding to low-frequency sub-bands) could be sent first for image previewing. Finally, spatial browsing of large images is possible through appropriate tile and/or partition selection. All these operations do not require any re-encoding but only byte-wise copy operations.

Performance



This image shows the (accentuated) difference between an image saved as JPEG 2000 (quality 50%) and the original.

Compared to the previous JPEG standard, JPEG 2000 delivers a typical compression gain in the range of 20%, depending on the image characteristics. Higher-resolution images tend to benefit more, where JPEG-2000's spatial-redundancy prediction can contribute more to the compression process. In very low-bitrate applications, studies have shown JPEG 2000 to be outperformed[44] by the intra-frame coding mode of H.264. Good applications for JPEG 2000 are large images, images with low-contrast edges — e.g., medical images.

File format and code stream

Similar to JPEG-1, JPEG 2000 defines both a file format and a code stream. Whereas the latter entirely describes the image samples, the former includes additional meta-information such as the resolution of the image or the color space that has been used to encode the image. JPEG 2000 images should — if stored as files — be boxed in the JPEG 2000 file format, where they get the **.jp2** extender. The part-2 extension to JPEG 2000, i.e., ISO/IEC 15444-2, also enriches this file format by including mechanisms for animation or composition of several code streams into one single image. Images in this extended file-format use the **.jpx** extension.

There is no standardized extension for code-stream data because code-stream data is not to be considered to be stored in files in the first place, though when done for testing purposes, the extension **.jpc** or **.j2k** appear frequently.

Metadata

For traditional JPEG, additional metadata, e.g. lighting and exposure conditions, is kept in an application marker in the Exif format specified by the JEITA. JPEG 2000 chooses a different route, encoding the same metadata in XML form. The reference between the Exif tags and the XML elements is standardized by the ISO TC42 committee in the standard 12234-1.4.

Extensible Metadata Platform can also be embedded in JPEG 2000.

Applications of JPEG 2000

Some markets and applications intended to be served by this standard are listed below:

- Consumer applications such as multimedia devices (e.g., digital cameras, personal digital assistants, 3G mobile phones, color facsimile, printers, scanners, etc.)
- Client/server communication (e.g., the Internet, Image database, Video streaming, video server, etc.)
- Military/surveillance (e.g., HD satellite images, Motion detection, network distribution and storage, etc.)
- Medical imagery, esp. the DICOM specifications for medical data interchange.
- Remote sensing
- High-quality frame-based video recording, editing and storage.
- Digital cinema

- JPEG 2000 has many design commonalities with the ICER image compression format that is used to send images back from the Mars rovers.
- World Meteorological Organization has built JPEG 2000 Compression into the new GRIB2 file format. The GRIB file structure is designed for global distribution of meteorological data. The implementation of JPEG 2000 compression in GRIB2 has reduced file sizes up to 80%.[45]

Comparison with PNG

Although JPEG 2000 format supports lossless encoding, it is not intended to completely supersede today's dominant lossless image file formats.

The PNG (Portable Network Graphics) format is still more space-efficient in the case of images with many pixels of the same color, such as diagrams, and supports special compression features that JPEG 2000 does not.

Legal issues

JPEG 2000 is by itself licensed, but the contributing companies and organizations agreed that licenses for its first part — the core coding system — can be obtained free of charge from all contributors.

The JPEG committee has stated:

> It has always been a strong goal of the JPEG committee that its standards should be implementable in their baseline form without payment of royalty and license fees... The up and coming JPEG 2000 standard has been prepared along these lines, and agreement reached with over 20 large organizations holding many patents in this area to allow use of their intellectual property in connection with the standard without payment of license fees or royalties.[46]

However, the JPEG committee has also noted that undeclared and obscure submarine patents may still present a hazard:

> It is of course still possible that other organizations or individuals may claim intellectual property rights that affect implementation of the standard, and any implementers are urged to carry out their own searches and investigations in this area.[47]

Because of this statement, controversy remains in the software community concerning the legal status of the JPEG 2000 standard.

JPEG 2000 is included in most Linux distributions.

Related standards

Several additional parts of the JPEG 2000 standard exist; Amongst them are ISO/IEC 15444-2:2000, JPEG 2000 extensions defining the **.jpx** file format, featuring for example Trellis quantization, an extended file format and additional color spaces[48] , ISO/IEC 15444-4:2000, the reference testing and ISO/IEC 15444-6:2000, the compound image file format (**.jpm**), allowing compression of compound text/image graphics.[49]

Extensions for secure image transfer, *JPSEC* (ISO/IEC 15444-8), enhanced error-correction schemes for wireless applications, *JPWL* (ISO/IEC 15444-11) and extensions for encoding of volumetric images, *JP3D* (ISO/IEC 15444-10) are also already available from the ISO.

JPIP protocol for streaming JPEG 2000 images

In 2005, a JPEG 2000 based image browsing protocol, called JPIP has been published as ISO/IEC 15444-9.[50] Within this framework, only selected regions of potentially huge images have to be transmitted from an image server on the request of a client, thus reducing the required bandwidth.

Motion JPEG 2000

Motion JPEG 2000 is defined in ISO/IEC 15444-3 and in ITU-T T.802[51] . It specifies the use of the JPEG 2000 codec for timed sequences of images (motion sequences), possibly combined with audio, and composed into an overall presentation.[52] [53] It also defines a file format, based on ISO base media file format (ISO 15444-12). Filename extensions for Motion JPEG 2000 video files are **.mj2** and **.mjp2** according to RFC 3745.

Motion JPEG 2000 (often referenced as MJ2 or MJP2) also is under consideration as a digital archival format by the Library of Congress. It is an open ISO standard and an advanced update to MJPEG (or MJ), which was based on the legacy JPEG format. Unlike common video codecs, such as MPEG-4, WMV, and DivX, MJ2 does not employ temporal or inter-frame compression. Instead, each frame is an independent entity encoded by either a lossy or lossless variant of JPEG 2000. Its physical structure does not depend on time ordering, but it does employ a separate profile to complement the data. For audio, it supports LPCM encoding, as well as various MPEG-4 variants, as "raw" or complement data.[54] [55]

ISO base media file format

ISO/IEC 15444-12 is identical with ISO/IEC 14496-12 (MPEG-4 Part 12) and it defines ISO base media file format. For example, Motion JPEG 2000 file format, MP4 file format or 3GP file format are also based on this ISO base media file format.[56] [57] [58] [59] [60]

GML JP2 Georeferencing

The Open Geospatial Consortium (OGC) has defined a metadata standard for georeferencing JPEG 2000 images with embedded XML using the Geography Markup Language (GML) format: *GML in JPEG 2000 for Geographic Imagery Encoding (GMLJP2)*, version 1.0.0, dated 2006-01-18 [61] .

JP2 and JPX files containing GMLJP2 markup can be located and displayed in the correct position on the Earth's surface by a suitable Geographic Information System (GIS), in a similar way to GeoTIFF images.

Application support

Applications

Application support for JPEG 2000

Program	Basic [62]		Advanced [62]		License
	Read	Write	Read	Write	
ACDSee	Yes	Yes	?	?	Proprietary
Accusoft Pegasus [63]	Yes	Yes	?	?	Proprietary
Adobe Photoshop [64]	Yes	Yes	Yes	Yes	Proprietary
Apple iPhoto	Yes	No	Yes	No	Proprietary
Apple Preview	Yes	Yes	Yes	?	Proprietary

Blender[65]	Yes	Yes	?	?	GPL
Corel Photo-Paint	Yes	Yes	Yes	Yes	Proprietary
DBGallery [66]	Yes	No	?	No	Proprietary
digiKam[67] [68] **(KDE**[69] **)**	Yes	Yes	?	?	GPL
FastStone Image Viewer	Yes	Yes	Yes	Yes	Proprietary
FastStone MaxView	Yes	No	Yes	No	Proprietary
Mozilla Firefox 3	via extension [70]	-	?	-	LGPL
GIMP	Yes[71]	No	?	No	GPL
Gwenview (KDE[69] **)**	Yes	Yes	?	?	GPL
ImageMagick	Yes	Yes	No	No	ImageMagick License [72]
IrfanView	Yes [73]	Partial [73]	No	No	Proprietary
KolourPaint (KDE[69] **)**	Yes	Yes	?	?	GPL
Mathematica	Yes	Yes	?	?	Proprietary
Matlab	via toolbox	via toolbox	via toolbox	via toolbox	Proprietary
Opera	via Quicktime	-	?	-	Proprietary
Paint Shop Pro	Yes	Yes	Yes	Yes	Proprietary
Pixel image editor	Yes	Yes	?	?	Proprietary
Safari	Yes	-	?	-	Proprietary
SilverFast	Yes	Yes	Yes	Yes	Proprietary
SView5	Yes	Yes	?	?	Proprietary
XnView [74]	Yes	Yes	Yes	Yes	Proprietary
Ziproxy	Yes	Yes	No	No	GPL

[1] The JPEG Still Picture Compression Standard (http://www.cis.temple.edu/~vasilis/Courses/CIS750/Papers/doc_jpeg_c_5.pdf) pp.6-7

[2] http://www.jpeg.org/JPEG2000.htm

[3] JPEG. "Joint Photographic Experts Group, JPEG2000" (http://www.jpeg.org/jpeg2000/index.html). . Retrieved 2009-11-01.

[4] IGN Standardization Team. "JPEG2000 (ISO 15444)" (http://eden.ign.fr/std/JPEG2000/index_html). . Retrieved 2009-11-01.

[5] http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_detail_ics.htm?csnumber=27687

[6] ISO. "ISO/IEC 15444-1:2004 - Information technology -- JPEG 2000 image coding system: Core coding system" (http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_detail_ics.htm?csnumber=27687). . Retrieved 2009-11-01.

[7] http://www.itu.int/rec/T-REC-T.800

[8] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=33160

[9] ISO. "ISO/IEC 15444-2:2004 - Information technology -- JPEG 2000 image coding system: Extensions" (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=33160). . Retrieved 2009-11-01.

[10] http://www.itu.int/rec/T-REC-T.801

[11] http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_detail_ics.htm?csnumber=33875

[12] ISO. "ISO/IEC 15444-3:2007 - Information technology -- JPEG 2000 image coding system: Motion JPEG 2000" (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=41570). . Retrieved 2009-11-01.

[13] http://www.itu.int/rec/T-REC-T.802

[14] http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_detail_ics.htm?csnumber=33876

[15] ISO. "ISO/IEC 15444-4:2004 - Information technology -- JPEG 2000 image coding system: Conformance testing" (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=39079). . Retrieved 2009-11-01.
[16] http://www.itu.int/rec/T-REC-T.803
[17] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=33877
[18] ISO. "ISO/IEC 15444-5:2003 - Information technology -- JPEG 2000 image coding system: Reference software" (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=33877). . Retrieved 2009-11-01.
[19] http://www.itu.int/rec/T-REC-T.804
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[21] ISO. "ISO/IEC 15444-6:2003 - Information technology -- JPEG 2000 image coding system -- Part 6: Compound image file format" (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=35458). . Retrieved 2009-11-01.
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[74] XnView supports JPEG 2000 compression only in MS Windows version (http://www.xnview.com/en/formats.html)

Libraries

Library support for JPEG 2000

Program	Basic		Advanced		Language	License
	Read	Write	Read	Write		
AccuRad J2KSuite (http://www.aware.com/imaging/accuradj2k.htm)	Yes	Yes	Yes	Yes	C++	Proprietary
FFmpeg	in progress [1]	in progress [1]	*?*	*?*	C	LGPL
GTK (from 2.14)	Yes	No	*?*	No	C/GTK	LGPL
JasPer	Yes	Yes	No	No	C	MIT License-style
JJ2000 (http://code.google.com/p/jj2000/)	Yes	Yes	No	No	Java	Special (similar to BSD-style)

Kakadu (http://www.kakadusoftware.com/)	Yes	Yes	Yes	Yes	C++	Proprietary
LEADTOOLS (http://www.leadtools.com/sdk/compression/jpeg2000.htm)	Yes	Yes	Yes	Yes	C, C++, .NET	Proprietary
OpenJPEG	Yes	Yes	?	?	C	BSD

[1] not merged to main repository, only in soc repository (http://svn.mplayerhq.hu/soc/jpeg2000/)

See also

- Comparison of graphics file formats
- DjVu — a compression format that also uses wavelets and that is designed for use on the web.
- ECW — a wavelet compression format that compares well to JPEG 2000.
- QuickTime — a multimedia framework, application and web browser plugin developed by Apple, capable of encoding, decoding and playing various multimedia files (including JPEG 2000 images by default).
- MrSID — a wavelet compression format that compares well to JPEG 2000
- PGF — a fast wavelet compression format that compares well to JPEG 2000
- JPIP — JPEG 2000 Interactive Protocol

References

- Official JPEG 2000 page (http://www.jpeg.org/JPEG2000.htm)
- Final Committee Drafts of JPEG 2000 standard (http://www.jpeg.org/jpeg2000/CDs15444.html) (as the official JPEG 2000 standard is not freely available, the final drafts are the most accurate freely available documentation about this standard)
- Gormish Notes on JPEG 2000 (http://www.crc.ricoh.com/~gormish/jpeg2000.html)
- Technical overview of JPEG 2000 (http://www.rii.ricoh.com/~gormish/pdf/dcc2000_jpeg2000_note.pdf) (PDF)
- Everything you always wanted to know about JPEG 2000 - published by intoPIX in 2008 (http://www.intopix.com/pdf/JPEG 2000 Handbook.pdf) (PDF)

External links

- RFC 3745, MIME Type Registrations for JPEG 2000 (ISO/IEC 15444)
- Official JPEG 2000 website (http://www.jpeg.org/JPEG2000.htm)
- All published books about JPEG 2000 (http://www.watermarkingworld.com/books_list?k=Jpeg2000)
- JPEG2000 Solutions: LuraTech (http://www.luratech.com)
- JPEG2000 Compression for Medical Imaging: Aware, Inc. (http://www.aware.com/imaging/accuradj2k.htm)

JPEG 2000 comparisons

- Side-by side comparison of appearance of 16k JPEG and JPEG 2000 files (http://www.fnordware.com/j2k/jp2samples.html)
- JPEG and JPEG 2000 Artifacts (http://kt.ijs.si/aleks/jpeg/artifacts.htm)

Operations on images

Linear filter

A **linear filter** applies a linear operator to a time-varying input signal. Linear filters are very common in electronics and digital signal processing (see the article on electronic filters), but they can also be found in mechanical engineering and other technologies.

They are often used to eliminate unwanted frequencies from an input signal or to select a desired frequency among many others. There are a wide range of types of filters and filter technologies, of which this article will present an overview.

Regardless of whether they are electronic, electrical, or mechanical, or what frequency ranges or timescales they work on, the mathematical theory of linear filters is universal.

Classification by transfer function

Impulse response

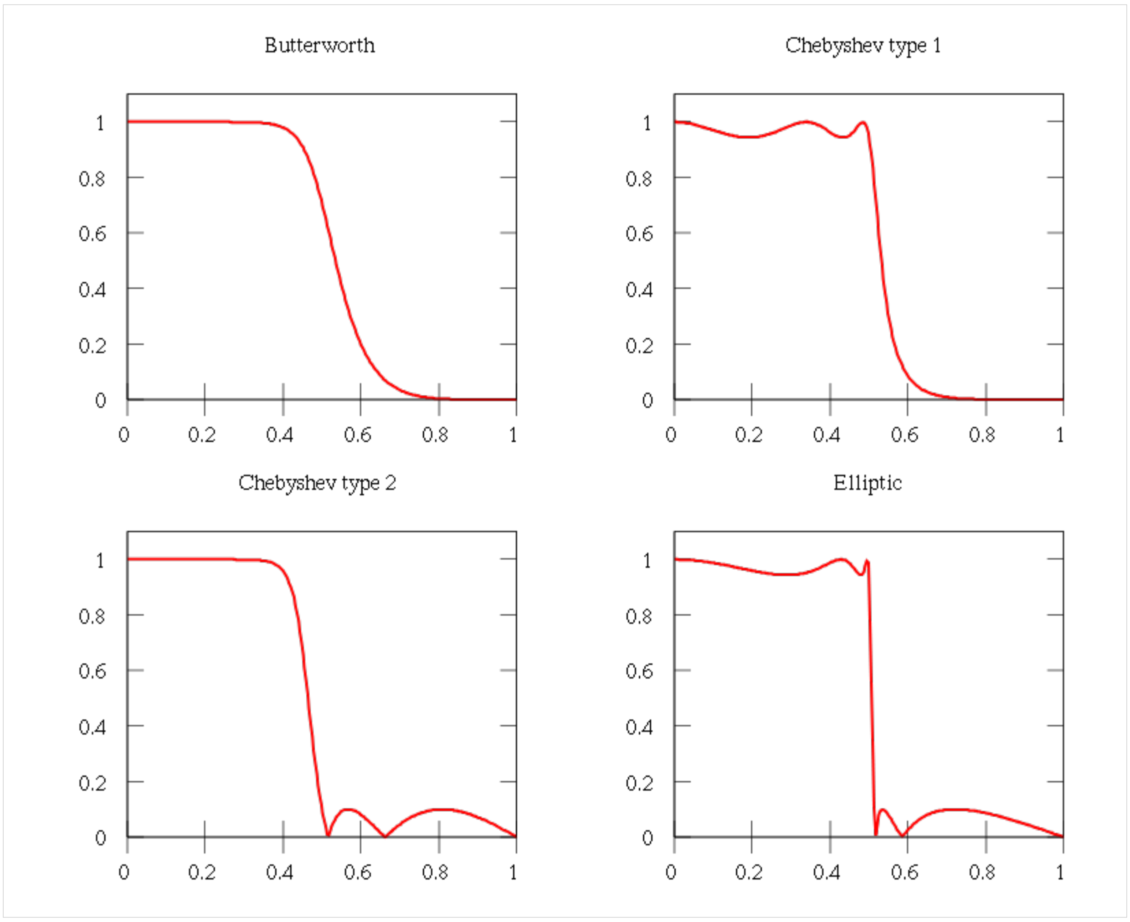
Linear filters can be divided into two classes: infinite impulse response (IIR) and finite impulse response (FIR) filters.

- An FIR filter (which may only be implemented in discrete time) may be described as a weighted sum of delayed inputs. For such a filter, if the input becomes zero at any time, then the output will eventually become zero as well, as soon as enough time has passed so that all the delayed inputs are zero, too. Therefore, the impulse response lasts only a finite time, and this is the reason for the name *finite impulse response*. A discrete-time transfer function of such a filter contains only poles at the origin (i.e., delays) and zeros; it cannot have off-origin poles.
- For an IIR filter, by contrast, if the input is set to 0 and the initial conditions are non-zero, then the set of time where the output is non-zero will be unbounded; the filter's energy will decay but will be ever present. Therefore, the impulse response extends to infinity, and the filter is said to have an *infinite impulse response*. There are no special restrictions on the transfer function of an IIR filter; it can have arbitrary poles and zeros, and it need not be expressible as a rational transfer function (for example, a sinc filter).

Until about the 1970s, only analog IIR filters were practical to construct. The distinction between FIR and IIR filters is generally applied only in the discrete-time domain. Because digital systems necessarily have discrete-time domains, both FIR and IIR filters are straightforward to implement digitally. Analog FIR filters can be built with analog delay lines.

Frequency response

Here is an image comparing the Fourier transform (i.e., "frequency response") of several popular continuous-time IIR filters: Butterworth, Chebyshev, and elliptic filters. The filters in this illustration are all fifth-order low-pass filters.



As is clear from the image, elliptic filters are sharper than the others, but they show ripples in their passband.

There are several common kinds of linear filters:

- A low-pass filter passes low frequencies.
- A high-pass filter passes high frequencies.
- A band-pass filter passes a limited range of frequencies.
- A band-stop filter passes all frequencies except a limited range.
- An all-pass filter passes all frequencies, but alters the phase relationship among them.
- A notch filter is a specific type of band-stop filter that acts on a particularly narrow range of frequencies.
- Some filters are not designed to stop any frequencies, but instead to gently vary the amplitude response at different frequencies: filters used as pre-emphasis filters, equalizers, or tone controls are good examples of this

Band-stop and bandpass filters can be constructed by combining low-pass and high-pass filters. A popular form of 2 pole filter is the Sallen-Key type. This is able to provide low-pass, band-pass, and high pass versions. A particular bandform of filter can be obtained by transformation of a prototype filter of that class.

Mathematics of filter design

Linear analog electronic filters
[1]

LTI system theory describes linear *time-invariant* (LTI) filters of all types. LTI filters can be completely described by their frequency response and phase response, the specification of which uniquely defines their impulse response, and *vice versa*. From a mathematical viewpoint, continuous-time IIR LTI filters may be described in terms of linear differential equations, and their impulse responses considered as Green's functions of the equation. Continuous-time LTI filters may also be described in terms of the Laplace transform of their impulse response, which allows all of the characteristics of the filter to be analyzed by considering the pattern of poles and zeros of their Laplace transform in the complex plane. Similarly, discrete-time LTI filters may be analyzed via the Z-transform of their impulse response.

Before the advent of computer filter synthesis tools, graphical tools such as Bode plots and Nyquist plots were extensively used as design tools. Even today, they are invaluable tools to understanding filter behavior. Reference books[2] had extensive plots of frequency response, phase response, group delay, and impulse response for various types of filters, of various orders. They also contained tables of values showing how to implement such filters as RLC ladders - very useful when amplifying elements were expensive compared to passive components. Such a ladder can also be designed to have minimal sensitivity to component variation[3] a property hard to evaluate without computer tools.

Many different analog filter designs have been developed, each trying to optimise some feature of the system response. For practical filters, a custom design is sometimes desirable, that can offer the best tradeoff between different design criteria, which may include component count and cost, as well as filter response characteristics.

These descriptions refer to the *mathematical* properties of the filter (that is, the frequency and phase response). These can be *implemented* as analog circuits (for instance, using a Sallen Key filter topology, a type of active filter), or as algorithms in digital signal processing systems.

Digital filters are much more flexible to synthesize and use than analog filters, where the constraints of the design permits their use. Notably, there is no need to consider component tolerances, and very high Q levels may be obtained.

FIR digital filters may be implemented by the direct convolution of the desired impulse response with the input signal. They can easily be designed to give a matched filter for any arbitrary pulse shape.

IIR digital filters are often more difficult to design, due to problems including dynamic range issues, quantization noise and instability. Typically digital IIR filters are designed as a series of digital biquad filters.

All low-pass second-order continuous-time filters have a transfer function given by

$$H(s) = \frac{K\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}.$$

All band-pass second-order continuous-time have a transfer function given by

$$H(s) = \frac{K\frac{\omega_0}{Q}s}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}.$$

where

- *K* is the gain (low-pass DC gain, or band-pass mid-band gain) (*K* is 1 for passive filters)
- *Q* is the Q factor
- ω_0 is the center frequency
- $s = \sigma + j\omega$ is the complex frequency

See also

- Filter design
- Laplace transform
- Green's function
- Prototype filter
- Z-transform
- System theory
    - LTI system theory
- Nonlinear filter
- Wiener filter
- Gabor filter

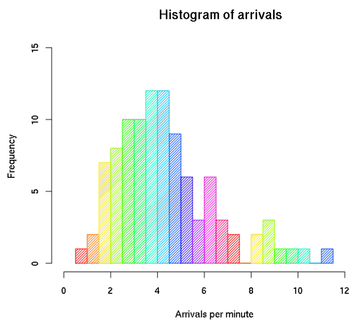
Further reading

- Williams, Arthur B & Taylor, Fred J (1995). *Electronic Filter Design Handbook*. McGraw-Hill. ISBN 0-07-070441-4.
- National Semiconductor AN-779 [4] application note describing analog filter theory
- Lattice AN6017 [5] application note comparing and contrasting filters (in order of damping coefficient, from lower to higher values): Gaussian, Bessel, linear phase, Butterworth, Chebyshev, Legendre, elliptic. (with graphs).
- "Design and Analysis of Analog Filters: A Signal Processing Perspective" [6] by L. D. Paarmann

References

[1] http://en.wikipedia.org/wiki/Template:Linear
[2] A. Zverev, *Handbook of Filter Synthesis*, John Wiley and Sons, 1967, ISBN 0-471-98680-1
[3] Normally, computing sensitivities is a very laborious operation. But in the special case of an LC ladder driven by an impedance and terminated by a resistor, there is a neat argument showing the sensitivities are small. In such as case, the transmission at the maximum frequency(s) transfers the maximal possible energy to the output load, as determined by the physics of the source and load impedances. Since this point is a maximum, *all* derivatives with respect to *all* component values must be zero, since the result of changing *any* component value in *any* direction can only result in a reduction. This result only strictly holds true at the peaks of the response, but is roughly true at nearby points as well.
[4] http://www.national.com/an/AN/AN-779.pdf
[5] http://www.latticesemi.com/lit/docs/appnotes/pac/an6017.pdf
[6] http://books.google.com/books?id=l7oC-LJwyegC&pg=PA267&lpg=PA267&dq=%22legendre+filter%22&source=web&ots=xRLtCLfslz&sig=0Nw2zhb8Y7FSrylN3wDaoIMkekQ#PPA238,M1

Histogram

Histogram	
	
One of the Seven Basic Tools of Quality	
First described by	Karl Pearson
Purpose	To roughly assess the probability distribution of a given variable by depicting the frequencies of observations occurring in certain ranges of values

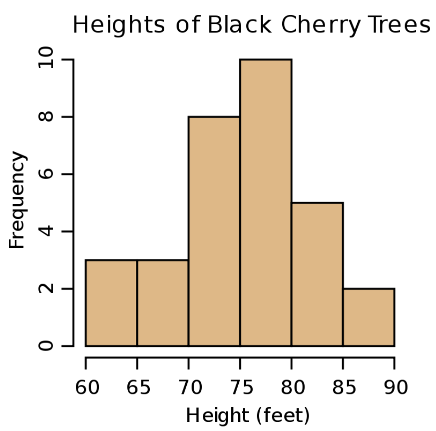
In statistics, a **histogram** is a graphical display of tabular frequencies, shown as adjacent rectangles. Each rectangle is erected over an interval, with an area equal to the frequency of the interval. The height of a rectangle is also equal to the frequency density of the interval, i.e. the frequency divided by the width of the interval. The total area of the histogram is equal to the number of data. A histogram may also be based on the relative frequencies instead. It then shows what proportion of cases fall into each of several categories (a form of data binning), and the total area then equals 1. The categories are usually specified as consecutive, non-overlapping intervals of some variable. The categories (intervals) must be adjacent, and often are chosen to be of the same size,[1] but not necessarily so.

Histograms are used to plot density of data, and often for density estimation: estimating the probability density function of the underlying variable. The total area of a histogram used for probability density is always normalized to 1. If the length of the intervals on the *x*-axis are all 1, then a histogram is identical to a relative frequency plot.

An alternative to the histogram is kernel density estimation, which uses a kernel to smooth samples. This will construct a smooth probability density function, which will in general more accurately reflect the underlying variable.

The histogram is one of the seven basic tools of quality control.[2]

Etymology



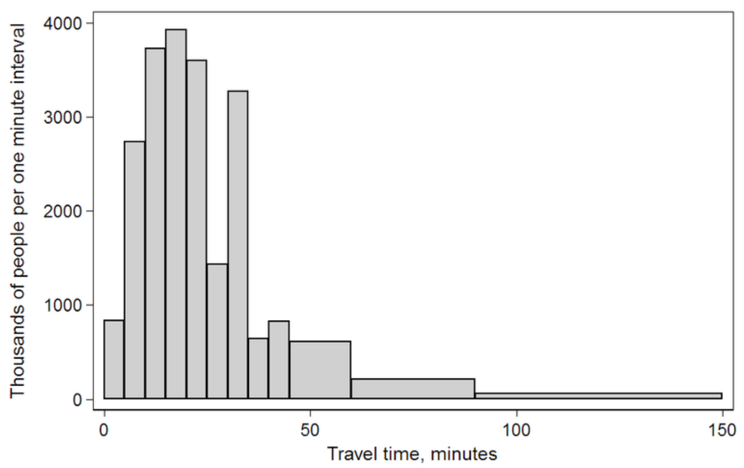
An example histogram of the heights of 31 Black Cherry trees.

The etymology of the word *histogram* is uncertain. Sometimes it is said to be derived from the Greek *histos* 'anything set upright' (as the masts of a ship, the bar of a loom, or the vertical bars of a histogram); and *gramma* 'drawing, record, writing'. It is also said that Karl Pearson, who introduced the term in 1895, derived the name from "historical diagram".

[3]

Examples

As an example we consider data collected by the U.S. Census Bureau on time to travel to work (2000 census, [4], Table 2). The census found that there were **124 million people** who work outside of their homes. An interesting feature of this graph is that the number recorded for "at least 30 but less than 35 minutes" is higher than for the bands on either side. This is likely to have arisen from people rounding their reported journey time. This rounding is a common phenomenon when collecting data from people.



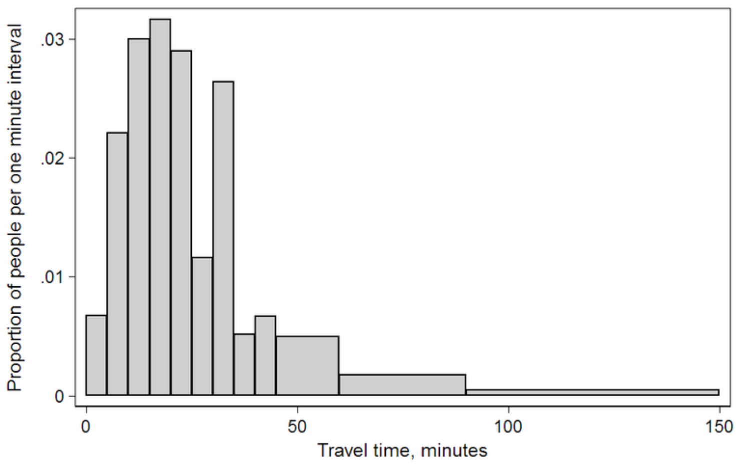
Histogram of travel time, US 2000 census. Area under the curve equals the total number of cases. This diagram uses Q/width from the table.

Data by absolute numbers

Interval	Width	Quantity	Quantity/width
0	5	4180	836
5	5	13687	2737
10	5	18618	3723
15	5	19634	3926
20	5	17981	3596
25	5	7190	1438
30	5	16369	3273
35	5	3212	642

40	5	4122	824
45	15	9200	613
60	30	6461	215
90	60	3435	57

This histogram shows the number of cases per unit interval so that the height of each bar is equal to the proportion of total people in the survey who fall into that category. The area under the curve represents the total number of cases (124 million). This type of histogram shows absolute numbers.



Histogram of travel time, US 2000 census. Area under the curve equals 1. This diagram uses Q/total/width from the table.

Data by proportion

Interval	Width	Quantity (Q)	Q/total/width
0	5	4180	0.0067
5	5	13687	0.0221
10	5	18618	0.0300
15	5	19634	0.0316
20	5	17981	0.0290
25	5	7190	0.0116
30	5	16369	0.0264
35	5	3212	0.0052
40	5	4122	0.0066
45	15	9200	0.0049
60	30	6461	0.0017
90	60	3435	0.0005

This histogram differs from the first only in the vertical scale. The height of each bar is the decimal percentage of the total that each category represents, and the total area of all the bars is equal to 1, the decimal equivalent of 100%. The curve displayed is a simple density estimate. This version shows proportions, and is also known as a unit area histogram.

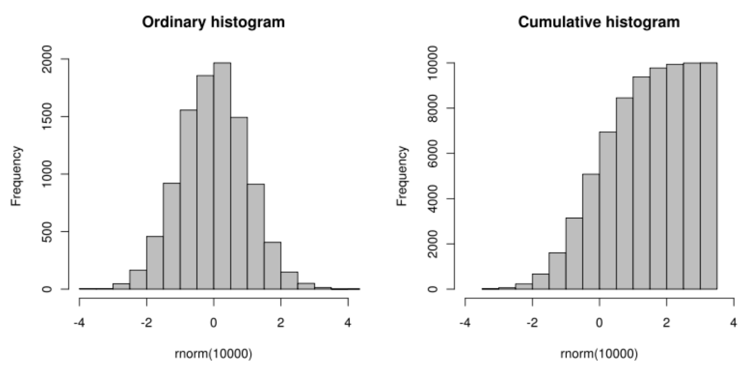
In other words a histogram represents a frequency distribution by means of rectangles whose widths represent class intervals and whose areas are proportional to the corresponding frequencies. The intervals are placed together in order to show that the data represented by the histogram while being exclusive is also continuous. (E.g., in a histogram it is possible to have two connnecting intervals of 10.5-20.5 and 20.5-33.5, but not two connecting intervals of 10.5-20.5 and 22.5-32.5. Empty intervals are represented as empty and not skipped.)[5]

Activities and demonstrations

The SOCR resource pages contain a number of hands-on interactive activities demonstrating the concept of a histogram, histogram construction [6] and manipulation [7] using Java applets and charts [8].

Mathematical definition

In a more general mathematical sense, a histogram is a mapping m_i that counts the number of observations that fall into various disjoint categories (known as *bins*), whereas the graph of a histogram is merely one way to represent a histogram. Thus, if we let n be the total number of observations and k be the total number of bins, the histogram m_i meets the following conditions:



An ordinary and a cumulative histogram of the same data. The data shown is a random sample of 10,000 points from a normal distribution with a mean of 0 and a standard deviation of 1.

$$n = \sum_{i=1}^{k} m_i.$$

Cumulative histogram

A cumulative histogram is a mapping that counts the cumulative number of observations in all of the bins up to the specified bin. That is, the cumulative histogram M_i of a histogram m_j is defined as:

$$M_i = \sum_{j=1}^{i} m_j.$$

Number of bins and width

There is no "best" number of bins, and different bin sizes can reveal different features of the data. Some theoreticians have attempted to determine an optimal number of bins, but these methods generally make strong assumptions about the shape of the distribution. You should always experiment with bin widths before choosing one (or more) that illustrate the salient features in your data.

The number of bins k can be assigned directly or can be calculated from a suggested bin width h as:

$$k = \left\lceil \frac{\max x - \min x}{h} \right\rceil.$$

The braces indicate the ceiling function.

Sturges' formula[9]

$$k = \lceil \log_2 n + 1 \rceil,$$

which implicitly bases the bin sizes on the range of the data, and can perform poorly if $n < 30$.

Scott's choice[10]

$$h = \frac{3.5\sigma}{n^{1/3}},$$

where σ is the sample standard deviation.

Square-Root Choice

$$k = \sqrt{n},$$

which takes the square root of the number of data points in the sample (used by Excel histograms and many others)

Freedman–Diaconis' choice[11]

$$h = 2\frac{\mathrm{IQR}(x)}{n^{1/3}},$$

which is based on the interquartile range. A good discussion of this and other rules for choice of bin widths is in *Modern Applied Statistics with S*, § 5.6: Density Estimation.[12]

See also

- Data binning
- Freedman–Diaconis rule
- Image histogram
- Density estimation
- Kernel density estimation, a smoother but more complex method of density estimation

Further reading

- Lancaster, H.O. *An Introduction to Medical Statistics.* John Wiley and Sons. 1974. ISBN 0 471 51250-8

External links

- Journey To Work and Place Of Work [13] *(location of census document cited in example)*
- Understanding histograms in digital photography [14]
- Histograms: Construction, Analysis and Understanding with external links and an application to particle Physics. [15]
- A Method for Selecting the Bin Size of a Histogram [16]
- Interactive histogram generator [17]
- Matlab function to plot nice histograms [18]

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[6] http://wiki.stat.ucla.edu/socr/index.php/SOCR_EduMaterials_ModelerActivities_MixtureModel_1

[7] http://wiki.stat.ucla.edu/socr/index.php/SOCR_EduMaterials_Activities_PowerTransformFamily_Graphs

[8] http://www.socr.ucla.edu/htmls/SOCR_Charts.html

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[12] W. N. Venables and B. D. Ripley: "Modern Applied Statistics with S", Springer, in (4thedition) section 5.6: *Density Estimation*

[13] http://www.census.gov/population/www/socdemo/journey.html

[14] http://www.luminous-landscape.com/tutorials/understanding-series/understanding-histograms.shtml

[15] http://quarknet.fnal.gov/toolkits/ati/histograms.html

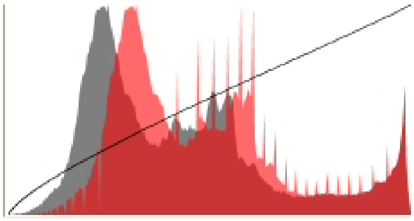
[16] http://2000.jukuin.keio.ac.jp/shimazaki/res/histogram.html

[17] http://www.shodor.org/interactivate/activities/histogram/

[18] http://www.mathworks.com/matlabcentral/fileexchange/27388-plot-and-compare-nice-histograms-by-default

Image histogram

Sunflower image



Histogram of Sunflower image

An **image histogram** is a type of histogram which acts as a graphical representation of the tonal distribution in a digital image.[1] It plots the number of pixels for each tonal value. By looking at the histogram for a specific image, a viewer will be able to judge the entire tonal distribution at a glance.

Image histograms are present on many modern digital cameras. Photographers can use them as an aid to show the distribution of tones captured, and whether image detail has been lost to blown-out highlights or blacked-out shadows.[2]

The horizontal axis of the graph represents the tonal variations, while the vertical axis represents the number of pixels in that particular tone.[1] The left side of the horizontal axis represents the black and dark areas, the middle represents medium grey, and the right hand side represents light and pure white areas. The vertical axis represents the size of the area that is captured in each one of these zones.

Image manipulation and histograms

Image editors typically have provisions to create a histogram of the image being edited. The histogram plots the number of pixels in the image (vertical axis) with a particular brightness value (horizontal axis). Algorithms in the digital editor allow the user to visually adjust the brightness value of each pixel and to dynamically display the results as adjustments are made.[3] Improvements in picture brightness and contrast can thus be obtained.

See also

- Histogram
- Image editing
- Color histogram, a multidimensional histogram of the distribution of color in an image
- Histogram equalization
- Histogram matching

References

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[2] Michael Freeman (2005). *The Digital SLR Handbook*. Ilex. ISBN 1904705-36-7.

[3] Martin Evening (2007). *Adobe Photoshop CS3 for Photographers: A Professional Image Editor's Guide...* (http://books.google.com/books?id=0XZO93ZcbqkC&pg=PA136&dq="image+histogram"&lr=&as_brr=0&ei=dvL2R--yFI2AsgPP7Z2FCg&sig=UoCi37U--m3IUzm6fUG-YB3za_Y#PPA136,M1). Focal Press. ISBN 0240520289. .

Color histogram

In image processing and photography, a **color histogram** is a representation of the distribution of colors in an image. For digital images, it is basically the number of pixels that have colors in each of a fixed list of color ranges, that span the image's color space, the set of all possible colors.

The color histogram can be built for any kind of color space, although the term is more often used for three-dimensional spaces like RGB or HSV. For monochromatic images, the term **intensity histogram** may be used instead. For multi-spectral images, where each pixel is represented by a *N*of measurements, each within its own wavelength range of the light spectrum, some of which may be outside the visible spectrum, the colour histogram is *N*-dimensional.

If the set of possible color values is sufficiently small, each of those colors may be placed on a range by itself; then the histogram is merely the count of pixels that have each possible color. Most often, the space is divided into an appropriate number of ranges, often arranged as a regular grid, each containing many similar color values. The color histogram may also be represented and/or displayed as a smooth function defined over the color space, that approximates the pixel counts.

Like other kinds of histograms, the color histogram is a statistic that can be viewed as an approximation of an underlying continuous distribution of colors values.

Overview

Color histograms are flexible constructs that can be built from images in various color spaces, whether RGB, rg chromaticity or any other color space of any dimension. A histogram of an image is produced first by discretization of the colors in the image into a number of bins, and counting the number of image pixels in each bin. For example, a Red–Blue chromaticity histogram can be formed by first normalizing color pixel values by dividing RGB values by R+G+B, then quantizing the normalized R and B coordinates into N bins each; say N = 4, which might yield a 2D histogram that looks like this table:

		red			
		0-63	64-127	128-191	192-255
blue	0-63	43	78	18	0
	64-127	45	67	33	2
	128-191	127	58	25	8
	192-255	140	47	47	13

Similarly a histogram can be made three-dimensional, though it is harder to display.[1]

The histogram provides a compact summarization of the distribution of data in an image. The color histogram of an image is relatively invariant with translation and rotation about the viewing axis, and varies only slowly with the angle of view.[2] By comparing histograms signatures of two images and matching the color content of one image with the other, the color histogram is particularly well suited for the problem of recognizing an object of unknown position and rotation within a scene. Importantly, translation of an RGB image into the illumination invariant rg-chromaticity space allows the histogram to operate well in varying light levels.

The main drawback of histograms for classification is that the representation is dependent of the color of the object being studied, ignoring its shape and texture. Color histograms can potentially be identical for two images with different object content which happens to share color information. Conversely, without spatial or shape information, similar objects of different color may be indistinguishable based solely on color histogram comparisons. There is no way to distinguish a red and white cup from a red and white plate. Put another way, histogram-based algorithms have no concept of a generic 'cup', and a model of a red and white cup is no use when given an otherwise identical blue and white cup. Another problem is that color histograms have high sensitivity to noisy interference such as lighting intensity changes and quantization errors. High dimensionality(bins) of color histograms are also another issue. Some color histogram feature spaces often occupy more than one hundred dimensions[8].

Some of the proposed solutions have been color histogram intersection, color constant indexing, cumulative color histogram, quadratic distance, and last but not least color correlograms [8]. Check out the external link to Standford for in depth look at the equations.

Although there are drawbacks of using histograms for indexing/classifications, using color in a real-time system has several relative advantages. One is that color information is faster to compute, compared to other "invariants." It has been shown in some cases that color can a be an efficient method for identifying objects of known location and appearances (refer to external link for findings in study)[8].

Further research into the relationship between color histograms data to the physical properties of the objects in an image has shown they can represent not only object color and illumination but relate to surface roughness and image geometry and provide improved estimate of illumination and object color.[3]

Usually **Euclidean distance**, **histogram intersection**, or **cosine** or **quadratic distances** are used for the calculation of the images’ similarity rating.[4] . Any of these values does not reflect the similarity rate of two images in itself. It is useful only with comparison to other similar values. This is the reason that all the practical implementations of content-based image retrieval must complete computation of all images from the database. It is the main disadvantage of these implementations.

Other approach to representative color image content is 2D-color histogram. **2D-color histogram** considers the relation between the pixel pair colors (not only the lighting component).[5] 2D-color histogram is a two-dimensional array, Cmax*Cmax, where Cmax is the number of colors that was used in the phase of color quantization. These arrays are treated as matrices, each element of which stores a normalized count of pixel pairs, with each color corresponding to the index of an element in each pixel neighbourhood. For comparison of 2D-color histograms it is suggested calculating their **correlation**, because a 2D-color histogram, constructed as described above, is a random vector (in other words, a multidimensional random value). While creating a set of final images, the images should be arranged in decreasing order of the correlation coefficient. Correlation coefficient may be used also for color histograms comparison. Retrieval results with correlation coefficient are better than with other metrics.[6]

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Intensity histogram of continuous data

The idea of an intensity histogram can be generalized to continuous data, say audio signals represented by real functions or images represented by functions with two-dimensional domain.

Let $f \in L^1(\mathbb{R}^n)$ (see Lebesgue space), then the cumulative histogram operator H can be defined by:

$$H(f)(y) = \mu\{x : f(x) \leq y\} .$$

μ is the Lebesgue measure of sets. $H(f)$ in turn is a real function. The (non-cumulative) histogram is defined as its derivative.

$$h(f) = H(f)' .$$

External links

- 3D Color Inspector/Color Histogram [7], by Kai Uwe Barthel [8]. (Free Java applet.)
- QBIC Image Retrieval [9], by State Hermitage Museum
- Standford Student Project on Image Based Retrieval [10] - more in depth look at equations/application
- MATLAB/Octave code for plotting Color Histograms and Color Clouds [11] - The source code can be ported to other languages

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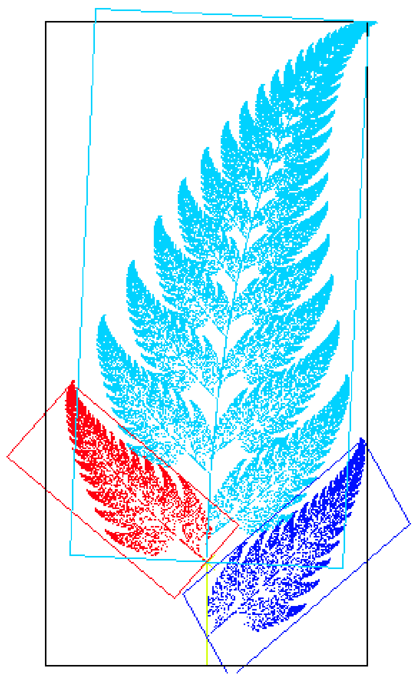
[7] http://rsb.info.nih.gov/ij/plugins/color-inspector.html
[8] http://www.f4.fhtw-berlin.de/~barthel/
[9] http://www.hermitagemuseum.org/fcgi-bin/db2www/qbicSearch.mac/qbic?selLang=English
[10] http://scien.stanford.edu/class/psych221/projects/02/sojeong/
[11] http://www.mathworks.com/matlabcentral/fileexchange/20757

Affine transformation

In geometry, an **affine transformation** or **affine map** or an **affinity** (from the Latin, *affinis*, "connected with") between two vector spaces (strictly speaking, two affine spaces) consists of a linear transformation followed by a translation:



An image of a fern which exhibits affine self-similarity

$$x \mapsto Ax + b.$$

In the finite-dimensional case each affine transformation is given by a matrix A and a vector *b*, satisfying certain properties described below.

Geometrically, an affine transformation in Euclidean space is one that preserves

1. The collinearity relation between points; i.e., three points which lie on a line continue to be collinear after the transformation
2. Ratios of distances along a line; i.e., for distinct collinear points $p_1,\ p_2,\ p_3$, the ratio $|p_2 - p_1|/|p_3 - p_2|$ is preserved

In general, an affine transformation is composed of linear transformations (rotation, scaling or shear) and a translation (or "shift"). Several linear transformations can be combined into a single one, so that the general formula given above is still applicable.

In the one-dimensional case, *A* and *b* are called, respectively, slope and intercept.

Representation

Ordinary vector algebra uses matrix multiplication to represent linear transformations, and vector addition to represent translations. Using an augmented matrix, it is possible to represent both using matrix multiplication. The technique requires that all vectors are augmented with a "1" at the end, and all matrices are augmented with an extra row of zeros at the bottom, an extra column—the translation vector—to the right, and a "1" in the lower right corner. If *A* is a matrix,

$$\begin{bmatrix} \vec{y} \\ 1 \end{bmatrix} = \begin{bmatrix} A & \vec{b} \\ 0, \ldots, 0 & 1 \end{bmatrix} \begin{bmatrix} \vec{x} \\ 1 \end{bmatrix}$$

is equivalent to the following

$$\vec{y} = A\vec{x} + \vec{b}.$$

This representation exhibits the set of all invertible affine transformations as the semidirect product of K^n and GL(*n*, *k*). This is a group under the operation of composition of functions, called the affine group.

Ordinary matrix-vector multiplication always maps the origin to the origin, and could therefore never represent a translation, in which the origin must necessarily be mapped to some other point. By appending a "1" to every vector, one essentially considers the space to be mapped as a subset of a space with an additional dimension. In that space, the original space occupies the subset in which the final index is 1. Thus the origin of the original space can be found at (0,0, ... 0, 1). A translation within the original space by means of a linear transformation of the higher-dimensional space is then possible (specifically, a shear transformation). This is an example of homogeneous coordinates.

The advantage of using homogeneous coordinates is that one can combine any number of affine transformations into one by multiplying the matrices. This device is used extensively by graphics software.

Properties

An affine transformation is invertible if and only if *A* is invertible. In the matrix representation, the inverse is:

$$\begin{bmatrix} A^{-1} & -A^{-1}\vec{b} \\ 0, \ldots, 0 & 1 \end{bmatrix}$$

The invertible affine transformations form the affine group, which has the general linear group of degree *n* as subgroup and is itself a subgroup of the general linear group of degree *n* + 1.

The similarity transformations form the subgroup where *A* is a scalar times an orthogonal matrix. If and only if the determinant of *A* is 1 or −1 then the transformation preserves area; these also form a subgroup. Combining both conditions we have the isometries, the subgroup of both where *A* is an orthogonal matrix.

Each of these groups has a subgroup of transformations which preserve orientation: those where the determinant of A is positive. In the last case this is in 3D the group of rigid body motions (proper rotations and pure translations).

For any matrix A the following propositions are equivalent:

- $A - I$ is invertible
- A does *not* have an eigenvalue equal to 1
- for all b the transformation has exactly one fixed point
- there is a b for which the transformation has exactly one fixed point
- affine transformations with matrix A can be written as a linear transformation with some point as origin

If there is a fixed point, we can take that as the origin, and the affine transformation reduces to a linear transformation. This may make it easier to classify and understand the transformation. For example, describing a transformation as a rotation by a certain angle with respect to a certain axis is easier to get an idea of the overall behavior of the transformation than describing it as a combination of a translation and a rotation. However, this depends on application and context. Describing such a transformation for an *object* tends to make more sense in terms of rotation about an axis through the center of that object, combined with a translation, rather than by just a rotation with respect to some distant point. As an example: "move 200 m north and rotate 90° anti-clockwise", rather than the equivalent "with respect to the point 141 m to the northwest, rotate 90° anti-clockwise".

Affine transformations in 2D without fixed point (so where A has eigenvalue 1) are:

- pure translations
- scaling in a given direction, with respect to a line in another direction (not necessarily perpendicular), combined with translation that is not purely in the direction of scaling; the scale factor is the other eigenvalue; taking "scaling" in a generalized sense it includes the cases that the scale factor is zero (projection) and negative; the latter includes reflection, and combined with translation it includes glide reflection.
- shear combined with translation that is not purely in the direction of the shear (there is no other eigenvalue than 1; it has algebraic multiplicity 2, but geometric multiplicity 1)

Affine transformation of the plane

To visualise the general affine transformation of the Euclidean plane, take labelled parallelograms $ABCD$ and $A'B'C'D'$. Whatever the choices of points, there is an affine transformation T of the plane taking A to A', and each vertex similarly. Supposing we exclude the degenerate case where $ABCD$ has zero area, there is a unique such affine transformation T. Drawing out a whole grid of parallelograms based on $ABCD$, the image $T(P)$ of any point P is determined by noting that $T(A) = A'$, T applied to the line segment AB is $A'B'$, T applied to the line segment AC is $A'C'$, and T respects scalar multiples of vectors based at A. [If A, E, F are collinear then the ratio length(AF)/length(AE) is equal to length($A'F'$)/length($A'E'$).] Geometrically T transforms the grid based on $ABCD$ to that based in $A'B'C'D'$.

Affine transformations don't respect lengths or angles; they multiply area by a constant factor

area of $A'\,B'\,C'\,D'$ / area of $ABCD$.

A given T may either be *direct* (respect orientation), or *indirect* (reverse orientation), and this may be determined by its effect on *signed* areas (as defined, for example, by the cross product of vectors).

Example of an affine transformation

The following equation expresses an affine transformation in GF(2) (with "+" representing XOR):

$$\{\,a'\,\} = M\{\,a\,\} + \{\,v\,\},$$

where [M] is the matrix

$$\begin{bmatrix}1&0&0&0&1&1&1&1\\1&1&0&0&0&1&1&1\\1&1&1&0&0&0&1&1\\1&1&1&1&0&0&0&1\\1&1&1&1&1&0&0&0\\0&1&1&1&1&1&0&0\\0&0&1&1&1&1&1&0\\0&0&0&1&1&1&1&1\end{bmatrix}$$

and $\{v\}$ is the vector

$$\begin{bmatrix}1\\1\\0\\0\\0\\1\\1\\0\end{bmatrix}.$$

For instance, the affine transformation of the element {a} = $x^7 + x^6 + x^3 + x$ = {11001010} in big-endian binary notation = {CA} in big-endian hexadecimal notation, is calculated as follows:

$$\begin{aligned}
a_0' &= a_0 \oplus a_4 \oplus a_5 \oplus a_6 \oplus a_7 \oplus 1 = 0 \oplus 0 \oplus 0 \oplus 1 \oplus 1 \oplus 1 = 1\\
a_1' &= a_0 \oplus a_1 \oplus a_5 \oplus a_6 \oplus a_7 \oplus 1 = 0 \oplus 1 \oplus 0 \oplus 1 \oplus 1 \oplus 1 = 0\\
a_2' &= a_0 \oplus a_1 \oplus a_2 \oplus a_6 \oplus a_7 \oplus 0 = 0 \oplus 1 \oplus 0 \oplus 1 \oplus 1 \oplus 0 = 1\\
a_3' &= a_0 \oplus a_1 \oplus a_2 \oplus a_3 \oplus a_7 \oplus 0 = 0 \oplus 1 \oplus 0 \oplus 1 \oplus 1 \oplus 0 = 1\\
a_4' &= a_0 \oplus a_1 \oplus a_2 \oplus a_3 \oplus a_4 \oplus 0 = 0 \oplus 1 \oplus 0 \oplus 1 \oplus 0 \oplus 0 = 0\\
a_5' &= a_1 \oplus a_2 \oplus a_3 \oplus a_4 \oplus a_5 \oplus 1 = 1 \oplus 0 \oplus 1 \oplus 0 \oplus 0 \oplus 1 = 1\\
a_6' &= a_2 \oplus a_3 \oplus a_4 \oplus a_5 \oplus a_6 \oplus 1 = 0 \oplus 1 \oplus 0 \oplus 0 \oplus 1 \oplus 1 = 1\\
a_7' &= a_3 \oplus a_4 \oplus a_5 \oplus a_6 \oplus a_7 \oplus 0 = 1 \oplus 0 \oplus 0 \oplus 1 \oplus 1 \oplus 0 = 1.
\end{aligned}$$

Thus, $\{a'\} = x^7 + x^6 + x^5 + x^3 + x^2 + 1$ = {11101101} = {ED}.

See also

- The transformation matrix for an affine transformation
- Affine geometry
- Homothetic transformation
- Similarity transformation
- Linear transformation (the second meaning is affine transformation in 1D)
- 3D projection
- Flat (geometry)

External links

- Geometric Operations: Affine Transform [1], R. Fisher, S. Perkins, A. Walker and E. Wolfart.
- Weisstein, Eric W., "Affine Transformation [2]" from MathWorld.
- *Affine Transform* [3] by Bernard Vuilleumier, Wolfram Demonstrations Project.
- Affine Transformation on PlanetMath [4]

References

[1] http://homepages.inf.ed.ac.uk/rbf/HIPR2/affine.htm
[2] http://mathworld.wolfram.com/AffineTransformation.html
[3] http://demonstrations.wolfram.com/AffineTransform/
[4] http://planetmath.org/encyclopedia/AffineTransformation.html

Scaling (geometry)

In Euclidean geometry, **uniform scaling** or **isotropic scaling**[1] is a linear transformation that enlarges or increases or diminishes objects; the scale factor is the same in all directions; it is also called a homothety. The result of uniform scaling is similar (in the geometric sense) to the original. A scale factor of 1 is normally allowed, so that congruent shapes are also classed as similar, but some school text books specifically exclude this possibility.

More general is **scaling** with a separate scale factor for each axis direction. **Non-uniform** or **anisotropic scaling** is obtained when at least one of the scaling factors is different from the others; a special case is **directional scaling** or **stretching** (in one direction). Non-uniform scaling changes the shape of the object; e.g. a square may change into a rectangle, or into a parallelogram if the sides of the square are not parallel to the scaling axes (the angles between lines parallel to the axes are preserved, but not all angles).

Matrix representation

A scaling can be represented by a scaling matrix. To scale an object by a vector $v = (v_x, v_y, v_z)$, each point $p = (p_x, p_y, p_z)$ would need to be multiplied with this scaling matrix:

$$S_v = \begin{bmatrix} v_x & 0 & 0 \\ 0 & v_y & 0 \\ 0 & 0 & v_z \end{bmatrix}.$$

As shown below, the multiplication will give the expected result:

$$S_v p = \begin{bmatrix} v_x & 0 & 0 \\ 0 & v_y & 0 \\ 0 & 0 & v_z \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} v_x p_x \\ v_y p_y \\ v_z p_z \end{bmatrix}.$$

Such a scaling changes the diameter of an object by a factor between the scale factors, the area by a factor between the smallest and the largest product of two scale factors, and the volume by the product of all three.

A scaling in the most general sense is any affine transformation with a diagonalizable matrix. It includes the case that the three directions of scaling are not perpendicular. It includes also the case that one or more scale factors are equal to zero (projection), and the case of one or more negative scale factors. The latter corresponds to a combination of scaling proper and a kind of reflection: along lines in a particular direction we take the reflection in the point of intersection with a plane that need not be perpendicular; therefore it is more general than ordinary reflection in the plane.

Using homogeneous coordinates

Often, it is more useful to use homogeneous coordinates, since translation cannot be accomplished with a 3-by-3 matrix. To scale an object by a vector $v = (v_x, v_y, v_z)$, each homogeneous vector $p = (p_x, p_y, p_z, 1)$ would need to be multiplied with this scaling matrix:

$$S_v = \begin{bmatrix} v_x & 0 & 0 & 0 \\ 0 & v_y & 0 & 0 \\ 0 & 0 & v_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

As shown below, the multiplication will give the expected result:

$$S_v p = \begin{bmatrix} v_x & 0 & 0 & 0 \\ 0 & v_y & 0 & 0 \\ 0 & 0 & v_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix} = \begin{bmatrix} v_x p_x \\ v_y p_y \\ v_z p_z \\ 1 \end{bmatrix}.$$

The scaling is uniform if and only if the scaling factors are equal. If all scale factors except one are 1 we have directional scaling.

Since the last component of a homogeneous coordinate can be viewed as the denominator of the other three components, a scaling by a common factor s can be accomplished by using this scaling matrix:

$$S_v = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \frac{1}{s} \end{bmatrix}.$$

For each homogeneous vector $p = (p_x, p_y, p_z, 1)$ we would have

$$S_v p = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \frac{1}{s} \end{bmatrix} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix} = \begin{bmatrix} p_x \\ p_y \\ p_z \\ \frac{1}{s} \end{bmatrix}$$

which would be homogenized to

$$\begin{bmatrix} sp_x \\ sp_y \\ sp_z \\ 1 \end{bmatrix}.$$

See also

- Scale (ratio)
- Scale (map)
- Scales of scale models
- Scale (disambiguation)
- Scaling in gravity
- Transformation matrix

External links

- Understanding 2D Scaling [2] and Understanding 3D Scaling [3] by Roger Germundsson, The Wolfram Demonstrations Project.

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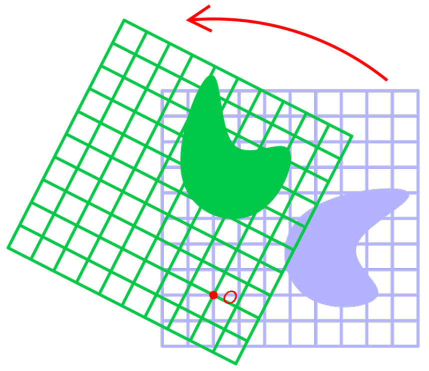
[2] http://demonstrations.wolfram.com/Understanding2DScaling/
[3] http://demonstrations.wolfram.com/Understanding3DScaling/

Rotation (mathematics)

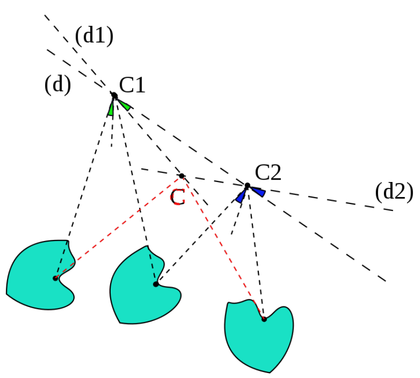


Rotation of an object in two dimensions around a point O.

In geometry and linear algebra, a **rotation** is a transformation in a plane or in space that describes the motion of a rigid body around a fixed point. A rotation is different from a translation, which has no fixed points, and from a reflection, which "flips" the bodies it is transforming. A rotation and the above-mentioned transformations are isometries; they leave the distance between any two points unchanged after the transformation.

It is important to know the frame of reference when considering rotations, as all rotations are described relative to a particular frame of reference. In general for any orthogonal transformation on a body in a coordinate system there is an inverse transformation which if applied to the frame of reference results in the body being at the same coordinates. For example in two dimensions rotating a body clockwise about a point keeping the axes fixed is equivalent to rotating the axes counterclockwise about the same point while the body is kept fixed.

Two dimensions

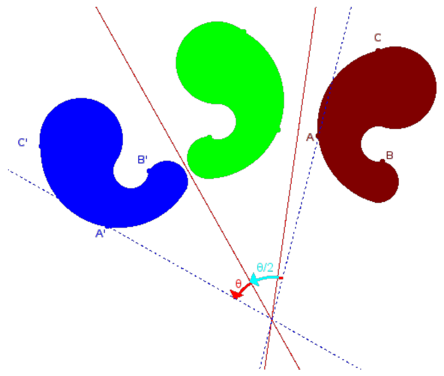


A plane rotation around a point followed by another rotation around a different point results in a total motion which is either a rotation (as in this picture), or a translation.

Only a single angle is needed to specify a rotation in two dimensions – the *angle of rotation*. To calculate the rotation two methods can be used, either matrix algebra or complex numbers. In each the rotation is acting to rotate an object counterclockwise through an angle θ about the origin.

Matrix algebra

To carry out a rotation using matrices the point (x, y) to be rotated is written as a vector, then multiplied by a matrix calculated from the angle, θ , like so:



A reflection against an axis followed by a reflection against a second axis not parallel to the first one results in a total motion that is a rotation around the point of intersection of the axes.

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}.$$

where (x', y') are the co-ordinates of the point after rotation, and the formulae for x' and y' can be seen to be

$$\begin{aligned} x' &= x\cos\theta - y\sin\theta \\ y' &= x\sin\theta + y\cos\theta. \end{aligned}$$

The vectors $\begin{bmatrix} x \\ y \end{bmatrix}$ and $\begin{bmatrix} x' \\ y' \end{bmatrix}$ have the same magnitude and are separated by an angle θ as expected.

Complex numbers

Points can also be rotated using complex numbers, as the set of all such numbers, the complex plane, is geometrically a two dimensional plane. the point (x, y) on the plane is represented by the complex number

$$z = x + iy$$

This can be rotated through an angle θ by multiplying it by $e^{i\theta}$, then expanding the product using Euler's formula as follows:

$$\begin{aligned} e^{i\theta} z &= (\cos\theta + i\sin\theta)(x + iy) \\ &= (x\cos\theta + iy\cos\theta + ix\sin\theta - y\sin\theta) \\ &= (x\cos\theta - y\sin\theta) + i(x\sin\theta + y\cos\theta) \\ &= x' + iy', \end{aligned}$$

which gives the same result as before,

$$\begin{aligned} x' &= x\cos\theta - y\sin\theta \\ y' &= x\sin\theta + y\cos\theta. \end{aligned}$$

Like complex numbers rotations in two dimensions are commutative, unlike in higher dimensions. They have only one degree of freedom, as such rotations are entirely determined by the angle of rotation.[1]

Three dimensions

Rotations in ordinary three-dimensional space differ than those in two dimensions in a number of important ways. Rotations in three dimensions are generally not commutative, so the order in which rotations are applied is important. They have three degrees of freedom, the same as the number of dimensions

A three dimensional rotation can be specified in a number of ways. The most usual methods are as follows.

Matrix algebra

As in two dimensions a matrix can be used to rotate a point (x, y, z) to a point (x', y', z'). The matrix used is a 3×3 matrix,

$$\mathbf{A} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix}$$

This is multiplied by a vector representing the point to give the result

$$\mathbf{A}\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix}\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}$$

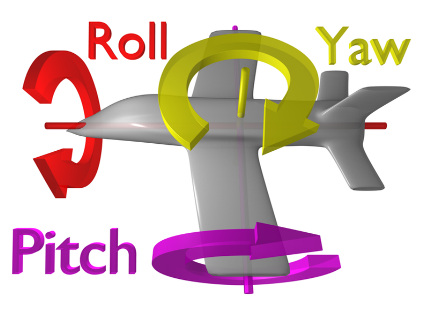
The matrix **A** is a member of the three dimensional special orthogonal group, SO(3), that is it is an orthogonal matrix with determinant 1. That it is an orthogonal matrix means that its rows are a set of orthogonal unit vectors (so they are an orthonormal basis) as are its columns, making it easy to spot and check if a matrix is a valid rotation matrix. The determinant must be 1 as if it is -1 (the only other possibility for an orthogonal matrix) then the transformation given by it is a reflection, improper rotation or inversion in a point, i.e. not a rotation.

Matrices are often used for doing transformations, especially when a large number of points are being transformed, as they are a direct representation of the linear operator. Rotations represented in other ways are often converted to matrices before being used. They can be extended to represent rotations and transformations at the same time using Homogeneous coordinates. Transformations in this space are represented by 4×4 matrices, which are not rotation matrices but which have a 3×3 rotation matrix in the upper left corner.

The main disadvantage of matrices is that they are more expensive to calculate and do calculations with. Also in calculations where numerical stability is a concern matrices can be more prone to it, so calculations to restore orthonormality, which are expensive to do for matrices, need to be done more often.

Euler angles

One way of generalising the two dimensional angle of rotation is to specify three rotation angles, carried out in turn about the three principal axes. They individually can be labelled yaw, pitch, and roll, but in mathematics are more often known by their mathematical name, Euler angles. They have the advantage of modelling a number of physical systems such as gimbals, and joysticks, so are easily visualised, and are a very compact way of storing a rotation. But they are difficult to use in calculations as even simple operations like combining rotations are expensive to do, and suffer from a form of gimbal lock where the angles cannot be uniquely calculated for certain rotations.



The principal axes of rotation in space

Axis angle

A second way of generalising the two dimensional angle of rotation is to specify an angle with the axis about which the rotation takes place. It can be used to model motion constrained by a hinges and Axles, and so is easily visualised, perhaps even more so than Euler angles. There are two ways to represent it;

- as a pair consisting of the angle and a unit vector for the axis, or
- as a vector obtained by multiplying the angle with this unit vector, called the rotation vector.

Usually the angle and axis pair is easier to work with, while the rotation vector is more compact, requiring only three numbers like Euler angles. But like Euler angles it is usually converted to another representation before being used.

Quaternions

Quaternions are in some ways the least intuitive representation of three dimensional rotations. They are not the three dimensional instance of a general approach, like matrices; nor are they easily related to real world models, like Euler angles or axis angles. But they are more compact than matrices and easier to work with than all other methods, so are often preferred in real world applications.

A rotation quaternion consists of four real numbers, constrained so the length of the quaternion considered as a vector is 1. This constraint limits the degree of freedom of the quaternion to three, as required. It can be thought of as a generalisation of the complex numbers, by e.g. the Cayley–Dickson construction, and generates rotations in a similar way by multiplication. But unlike matrices and complex numbers two multiplications are needed:

$$\mathbf{x}' = \mathbf{q}\mathbf{x}\mathbf{q}^{-1},$$

where **q** is the quaternion $\mathbf{q}^{-1}$ is its inverse and **x** is the vector treated as a quaternion. The quaternion can be related to the rotation vector form of the axis angle rotation by the exponential map over the quaternions,

$$\mathbf{q} = e^{\mathbf{v}/2},$$

Where **v** is the rotation vector treated as a quaternion.

Four dimensions

A general rotation in four dimensions has only one fixed point, the centre of rotation, and no axis of rotation. Instead the rotation has two mutually orthogonal planes of rotation, each of which is fixed in the sense that points in each plane stay within the planes. The rotation has two angles of rotation, one for each plane of rotation, through which points in the planes rotate. If these are ω_1 and ω_2 then all points not in the planes rotate through an angle between ω_1 and ω_2.

If $\omega_1 = \omega_2$ the rotation is a double rotation and all points rotate through the same angle so any two orthogonal planes can be taken as the planes of rotation. If one of ω_1 and ω_2 is zero, one plane is fixed and the rotation is simple. If both ω_1 and ω_2 are zero the rotation is the identity rotation.[2]

Rotations in four dimensions can be represented by 4th order orthogonal matrices, as a generalisation of the rotation matrix. Quaternions can also be generalised into four dimensions, as even Multivectors of the four dimensional Geometric algebra. A third approach, which only works in four dimensions, is to use a pair of unit quaternions.

Rotations in four dimensions have six degrees of freedom, most easily seen when two unit quaternions are used, as each has three degrees of freedom (they lie on the surface of a 3-sphere) and $2 \times 3 = 6$.

Relativity

One application of this is special relativity, as it can be considered to operate in a four dimensional space, spacetime, spanned by three space dimensions and one of time. In special relativity this space is linear and the four dimensional rotations, called Lorentz transformations, have practical physical interpretations.

If a simple rotation is only in the three space dimensions, i.e. about a plane that is entirely in space, then this rotation is the same as a spatial rotation in three dimensions. But a simple rotation about a plane spanned by a space dimension and a time dimension is a "boost", a transformation between two different reference frames, which together with other properties of spacetime determines the relativistic relationship between the frames. The set of these rotations forms the Lorentz group.[3]

Generalizations

Orthogonal matrices

The set of all matrices $M(\mathbf{v},\theta)$ described above together with the operation of matrix multiplication is called *rotation group*: SO(3).

More generally, coordinate rotations in any dimension are represented by orthogonal matrices. The set of all orthogonal matrices of the n-th dimension which describe proper rotations (determinant = +1), together with the operation of matrix multiplication, forms the *special orthogonal group*: SO(n).

Orthogonal matrices have real elements. The analogous complex-valued matrices are the unitary matrices. The set of all unitary matrices in a given dimension n forms a unitary group of degree n, U(n); and the subgroup of U(n) representing proper rotations forms a special unitary group of degree n, SU(n). The elements of SU(2) are used in quantum mechanics to rotate spin.

See also

- Rotation representation
- Spinor
- Charts on SO(3)
- Euler angles
- Vortical
- Rotation group
- Coordinate rotations and reflections
- Rodrigues' rotation formula
- Rotation matrix
- Orientation (geometry)

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External links

- Rotation about any point [4]

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[2] Lounesto 2001, pp. 85, 89.
[3] Hestenes 1999, pp. 580 - 588.
[4] http://www.euclideanspace.com/maths/geometry/affine/aroundPoint/

Color balance

In photography and image processing, **color balance** is the global adjustment of the intensities of the colors (typically red, green, and blue primary colors). An important goal of this adjustment is to render specific colors – particularly neutral colors – correctly; hence, the general method is sometimes called **gray balance**, **neutral balance**, or **white balance**. Color balance changes the overall mixture of colors in an image and is used for color correction; generalized versions of color balance are used to get colors other than neutrals to also appear correct or pleasing.

The left half shows the photo as it came from the digital camera. The right half shows the photo adjusted to make a gray surface neutral in the same light.

Image data acquired by sensors – either film or electronic image sensors – must be transformed from the acquired values to new values that are appropriate for color reproduction or display. Several aspects of the acquisition and display process make such color correction essential – including the fact that the acquisition sensors do not match the sensors in the human eye, that the properties of the display medium must be accounted for, and that the ambient viewing conditions of the acquisition differ from the display viewing conditions.

A seascape photograph at Clifton Beach, South Arm, Tasmania, Australia. The white balance has been adjusted towards the warm side for creative effect.

The color balance operations in popular image editing applications usually operate directly on the red, green, and blue channel pixel values,[1] [2] without respect to any color sensing or reproduction model. In shooting film, color balance is typically achieved by using color correction filters over the lights or on the camera lens.[3]

Generalized color balance

Sometimes the adjustment to keep neutrals neutral is called *white balance*, and the phrase *color balance* refers to the adjustment that in addition makes other colors in a displayed image appear to have the same general appearance as the colors in an original scene.[4] It is particularly important that neutral (gray, achromatic, white) colors in a scene appear neutral in the reproduction. Hence, the special case of balancing the neutral colors (sometimes *gray balance*, *neutral balance*, or *white balance*) is a particularly important – perhaps dominant – element of color balancing.

Normally, one would not use the phrase *color balance* to describe the adjustments needed to account for differences between the sensors and the human eye, or the details of the display primaries. *Color balance* is normally reserved to refer to correction for differences in the ambient illumination conditions. However, the algorithms for transforming the data do not always clearly separate out the different elements of the correction. Hence, it can be difficult to assign color balance to a specific step in the color correction process. Moreover, there can be significant differences in the color balancing goal. Some applications are created to produce an accurate rendering – as suggested above. In other applications, the goal of color balancing is to produce a pleasing rendering. This difference also creates difficulty in defining the color balancing processing operations.

Illuminant estimation and adaptation

Most digital cameras have a means to select a color correction based on the type of scene illumination, using either manual illuminant selection, or automatic white balance (AWB), or custom white balance. The algorithm that performs this analysis performs generalized color balancing, known as illuminant adaptation or chromatic adaptation.

Many methods are used to achieve color balancing. Setting a button on a camera is a way for the user to indicate to the processor the nature of the scene lighting. Another option on some cameras is a button which one may press when the camera is pointed at a gray card or other neutral object. This "custom white balance" step captures an image of the ambient light, and this information is helpful in controlling color balance.

There is a large literature on how one might estimate the ambient illumination from the camera data and then use this information to transform the image data. A variety of algorithms have been proposed, and the quality of these have been debated. A few examples and examination of the references therein will lead the reader to many others. Examples are Retinex, an artificial neural network[5] or a Bayesian method.[6]

Color balance and chromatic colors

Color balancing an image affects not only the neutrals, but other colors as well. An image that is not color balanced is said to have a color cast, as everything in the image appears to have been shifted towards one color or another.[7] Color balancing may be thought in terms of removing this color cast.

Color balance is also related to color constancy. Algorithms and techniques used to attain color constancy are frequently used for color balancing, as well. Color constancy is, in turn, related to chromatic adaptation. Conceptually, color balancing consists of two steps: first, determining the illuminant under which an image was captured; and second, scaling the components (e.g., R, G, and B) of the image or otherwise transforming the components so they conform to the viewing illuminant.

Viggiano found that white balancing in the camera's native RGB tended to produce less color inconstancy (i.e., less distortion of the colors) than in monitor RGB for over 4000 hypothetical sets of camera sensitivities.[8] This difference typically amounted to a factor of more than two in favor of camera RGB. This means that it is advantageous to get color balance right at the time an image is captured, rather than edit later on a monitor. If one must color balance later, balancing the raw image data will tend to produce less distortion of chromatic colors than balancing in monitor RGB.

Mathematics of color balance

Color balancing is sometimes performed on a three-component image (e.g., RGB) using a 3x3 matrix. This type of transformation is appropriate if the image were captured using the wrong white balance setting on a digital camera, or through a color filter.

Scaling monitor R, G, and B

In principle, one wants to scale all relative luminances in an image so that objects which are believed to be neutral appear so. If, say, a surface with R=240 was believed to be a white object, and if 255 is the count which corresponds to white, one could multiply all red values by 255/240. Doing analogously for green and blue would result, at least in theory, in a color balanced image. In this type of transformation the 3x3 matrix is a diagonal matrix.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 255/R'_w & 0 & 0 \\ 0 & 255/G'_w & 0 \\ 0 & 0 & 255/B'_w \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

where R , G , and B are the color balanced red, green, and blue components of a pixel in the image; R' , G' , and B' are the red, green, and blue components of the image before color balancing, and R'_w , G'_w , and B'_w are the red, green, and blue components of a pixel which is believed to be a white surface in the image before color balancing. This is a simple scaling of the red, green, and blue channels, and is why color balance tools in Photoshop and the GIMP have a white eyedropper tool. It has been demonstrated that performing the white balancing in the phosphor set assumed by sRGB tends to produce large errors in chromatic colors, even though it can render the neutral surfaces perfectly neutral.[8]

Scaling X, Y, Z

If the image may be transformed into CIE XYZ tristimulus values, the color balancing may be performed there. This has been termed a “wrong von Kries” transformation.[9] [10] Although it has been demonstrated to offer usually poorer results than balancing in monitor RGB, it is mentioned here as a bridge to other things. Mathematically, one computes:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_w/X'_w & 0 & 0 \\ 0 & Y_w/Y'_w & 0 \\ 0 & 0 & Z_w/Z'_w \end{bmatrix} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix}$$

where X , Y, and Z are the color-balanced tristimulus values; X_w , Y_w , and Z_w are the tristimulus values of the viewing illuminant (the white point to which the image is being transformed to conform to); X'_w , Y'_w , and Z'_w are the tristimulus values of an object believed to be white in the un-color-balanced image, and X', Y' , and Z' are the tristimulus values of a pixel in the un-color-balanced image. If the tristimulus values of the monitor primaries are in a matrix $\mathbf{P}$ so that:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{P} \begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix}$$

where L_R , L_G , and L_B are the un-gamma corrected monitor RGB, one may use:

$$\begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix} = \mathbf{P^{-1}} \begin{bmatrix} X_w/X'_w & 0 & 0 \\ 0 & Y_w/Y'_w & 0 \\ 0 & 0 & Z_w/Z'_w \end{bmatrix} \mathbf{P} \begin{bmatrix} L_{R'} \\ L_{G'} \\ L_{B'} \end{bmatrix}$$

Von Kries's method

Johannes von Kries, whose theory of rods and three different color-sensitive cone types in the retina has survived as the dominant explanation of color sensation for over 100 years, motivated the method of converting color to the LMS color space, representing the effective stimuli for the Long-, Medium-, and Short-wavelength cone types that are modeled as adapting independently. A 3x3 matrix converts RGB or XYZ to LMS, and then the three LMS primary values are scaled to balance the neutral; the color can then be converted back to the desired final color space:[11]

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 1/L'_w & 0 & 0 \\ 0 & 1/M'_w & 0 \\ 0 & 0 & 1/S'_w \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}$$

where L, M, and S are the color-balanced LMS cone tristimulus values; L'_w, M'_w, and S'_w are the tristimulus values of an object believed to be white in the un-color-balanced image, and L', M', and S' are the tristimulus values of a pixel in the un-color-balanced image.

Matrices to convert to LMS space were not specified by von Kries, but can be derived from CIE color matching functions and LMS color matching functions when the latter are specified; matrices can also be found in reference books.[11]

Scaling camera RGB

By Viggiano's measure, and using his model of gaussian camera spectral sensitivities, most camera RGB spaces performed better than either monitor RGB or XYZ.[8] If the camera's raw RGB values are known, one may use the 3x3 diagonal matrix:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 255/R'_w & 0 & 0 \\ 0 & 255/G'_w & 0 \\ 0 & 0 & 255/B'_w \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

and then convert to a working RGB space such as sRGB or Adobe RGB after balancing.

Preferred chromatic adaptation spaces

Comparisons of images balanced by diagonal transforms in a number of different RGB spaces have identified several such spaces that work better than others, and better than camera or monitor spaces, for chromatic adaptation, as measured by several color appearance models; the systems that performed statistically as well as the best on the majority of the image test sets used were the "Sharp", "Bradford", "CMCCAT", and "ROMM" spaces.[12]

General illuminant adaptation

The best color matrix for adapting to a change in illuminant is not necessarily a diagonal matrix in a fixed color space. It has long been known that if the space of illuminants can be described as a linear model with *N* basis terms, the proper color transformation will be the weighted sum of *N* fixed linear transformations, not necessarily consistently diagonalizable.[13]

See also

- Color temperature
- Gamma correction
- White point

External links

- White Balance [14] - Intro at nikondigital.org
- Understanding White Balance [15] - Tutorial
- Affine color balance with saturation, with code and on-line demonstration [16]

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Image registration

Image registration is the process of transforming different sets of data into one coordinate system. Data may be multiple photographs, data from different sensors, from different times, or from different viewpoints.[1] It is used in, computer vision, medical imaging, military automatic target recognition, and compiling and analyzing images and data from satellites. Registration is necessary in order to be able to compare or integrate the data obtained from these different measurements.

Registering and summing multiple exposures of the same scene improves signal to noise ratio, allowing to see things previously impossible to see.

Algorithm classification

Intensity-based vs feature-based

Image registration or image alignment algorithms can be classified into intensity-based and feature-based[2] . One of the images is referred to as the *reference* or *source* and the second image is referred to as the *target* or *sensed.* Image registration involves spatially transforming the target image to align with the reference image[2] .Intensity-based methods compare intensity patterns in images via correlation metrics, while feature-based methods find correspondence between image features such as points, lines, and contours[2] . Intensity-based methods register entire images or subimages. If subimages are registered, centers of corresponding subimages are treated as corresponding feature points. Feature-based method established correspondence between a number of points in images. Knowing the correspondence between a number of points in images, a transformation is then determined to map the target image to the reference images, thereby establishing point-by-point correspondence between the reference and target images[2] .

Transformation models

Image registration algorithms can also be classified according to the transformation models they use to relate the target image space to the reference image space. The first broad category of transformation models includes linear transformations, which include translation, rotation, scaling, and other affine transforms. Linear transformations are global in nature, thus, they cannot model local geometric differences between images[2] .

The second category of transformations allow 'elastic' or 'nonrigid' transformations. These transformations are capable of locally warping the target image to align with the reference image. Nonrigid transformations include radial basis functions (thin-plate or surface splines, multiquadrics, and compactly-supported transformations[2]), physical continuum models (viscous fluids), and large deformation models (diffeomorphisms).

Spatial vs. frequency domain methods

Spatial methods operate in the image domain, matching intensity patterns or features in images. Some of the feature matching algorithms are outgrowths of traditional techniques for performing manual image registration, in which an operator chooses corresponding control points (CPs) in images. When the number of control points exceeds the minimum required to define the appropriate transformation model, iterative algorithms like RANSAC can be used to robustly estimate the parameters of a particular transformation type (e.g. affine) for registration of the images.

Frequency-domain methods find the transformation parameters for registration of the images while working in the transform domain. Such methods work for simple transformations, such as translation, rotation, and scaling. Applying the Phase correlation method to a pair of images produces a third image which contains a single peak. The location of this peak corresponds to the relative translation between the images. Unlike many spatial-domain algorithms, the phase correlation method is resilient to noise, occlusions, and other defects typical of medical or satellite images. Additionally, the phase correlation uses the fast Fourier transform to compute the cross-correlation between the two images, generally resulting in large performance gains. The method can be extended to determine rotation and scaling differences between two images by first converting the images to log-polar coordinates. Due to properties of the Fourier transform, the rotation and scaling parameters can be determined in a manner invariant to translation.

Single- vs. multi-modality methods

Another classification can be made between single-modality and multi-modality methods. Single-modality methods tend to register images in the same modality acquired by the same scanner/sensor type, while multi-modality registration methods tended to register images acquired by different scanner/sensor types.

Multi-modality registration methods are often used in medical imaging as images of a subject are frequently obtained from different scanners. Examples include registration of brain CT/MRI images or whole body PET/CT images for tumor localization, registration of contrast-enhanced CT images against non-contrast-enhanced CT images for segmentation of specific parts of the anatomy, and registration of ultrasound and CT images for prostate localization in radiotherapy.

Automatic vs. interactive methods

Registration methods may be classified based on the level of automation they provide. Manual, interactive, semi-automatic, and automatic methods [3] have been developed. Manual methods provide tools to align the images manually. Interactive methods reduce user bias by performing certain key operations automatically while still relying on the user to guide the registration. Semi-automatic methods perform more of the registration steps automatically but depend on the user to verify the correctness of a registration. Automatic methods do not allow any user interaction and perform all registration steps automatically.

Similarity measures for image registration

Image similarities are broadly used in medical imaging. An image similarity measure quantifies the degree of similarity between intensity patterns in two images[2] . The choice of an image similarity measure depends on the modality of the images to be registered. Common examples of image similarity measures include cross-correlation, mutual information, sum of squared intensity differences, and ratio image uniformity. Mutual information and normalized mutual information are the most popular image similarity measures for registration of multimodality images. Cross-correlation, sum of squared intensity differences and ratio image uniformity are commonly used for registration of images in the same modality.

Uncertainty

There is a level of uncertainty associated with registering images that have any spatio-temporal differences. A confident registration with a measure of uncertainty is critical for many change detection applications such as medical diagnostics.

In remote sensing applications where a digital image pixel may represent several kilometers of spatial distance (such as NASA's LANDSAT imagery), an uncertain image registration can mean that a solution could be several kilometers from ground truth. Several notable papers have attempted to quantify uncertainty in image registration in order to compare results.[4] [5] However, many approaches to quantifying uncertainty or estimating deformations are computational intensive or are only applicable to limited sets of spatial transformations.

Applications

Image registration has applications in remote sensing (cartography updating), and computer vision. Due to the vast applications to which image registration can be applied, it is impossible to develop a general method that is optimized for all uses.

Medical image registration (for data of the same patient taken at different points in time such as change detection or tumor monitoring)) often additionally involves *elastic* (also known as *nonrigid*) registration to cope with deformation of the subject (due to breathing, anatomical changes, and so forth). Nonrigid registration of medical images can also be used to register a patient's data to an anatomical atlas, such as the Talairach atlas for neuroimaging.

It is also used in astrophotography to align images taken of space. Using control points (automatically or manually entered), the computer performs transformations on one image to make major features align with a second image.

Image registration is essential part of Panoramic image creation. There are many different techniques that can be implemented in real time and run on embedded devices like cameras and camera-phones.

See also

- Spatial normalization

External links

- Richard Szeliski, Image Alignment and Stitching: A Tutorial [6]. Foundations and Trends in Computer Graphics and Computer Vision, 2:1-104, 2006.
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Segmentation (image processing)

In computer vision, **segmentation** refers to the process of partitioning a digital image into multiple segments (sets of pixels, also known as superpixels). The goal of segmentation is to simplify and/or change the representation of an image into something that is more meaningful and easier to analyze.[1] Image segmentation is typically used to locate objects and boundaries (lines, curves, etc.) in images. More precisely, image segmentation is the process of assigning a label to every pixel in an image such that pixels with the same label share certain visual characteristics.

The result of image segmentation is a set of segments that collectively cover the entire image, or a set of contours extracted from the image (see edge detection). Each of the pixels in a region are similar with respect to some characteristic or computed property, such as color, intensity, or texture. Adjacent regions are significantly different with respect to the same characteristic(s).[1]

Applications

Some of the practical applications of image segmentation are:

- Medical Imaging[2]
  - Locate tumors and other pathologies
  - Measure tissue volumes
  - Computer-guided surgery
  - Diagnosis
  - Treatment planning
  - Study of anatomical structure
- Locate objects in satellite images (roads, forests, etc.)
- Face recognition
- Fingerprint recognition
- Traffic control systems
- Brake light detection
- Machine vision

Several general-purpose algorithms and techniques have been developed for image segmentation. Since there is no general solution to the image segmentation problem, these techniques often have to be combined with domain knowledge in order to effectively solve an image segmentation problem for a problem domain.

Clustering methods

The K-means algorithm is an iterative technique that is used to partition an image into *K* clusters. The basic algorithm is:

1. Pick *K* cluster centers, either randomly or based on some heuristic
2. Assign each pixel in the image to the cluster that minimizes the variance between the pixel and the cluster center
3. Re-compute the cluster centers by averaging all of the pixels in the cluster
4. Repeat steps 2 and 3 until convergence is attained (e.g. no pixels change clusters)

In this case, variance is the squared or absolute difference between a pixel and a cluster center. The difference is typically based on pixel color, intensity, texture, and location, or a weighted combination of these factors. *K* can be selected manually, randomly, or by a heuristic.

This algorithm is guaranteed to converge, but it may not return the optimal solution. The quality of the solution depends on the initial set of clusters and the value of *K*.

In statistics and machine learning, the k-means algorithm is clustering algorithm to partition n objects into k clusters, where $k < n$. It is similar to the expectation-maximization algorithm for mixtures of Gaussians in that they both attempt to find the centers of natural clusters in the data. The model requires that the object attributes correspond to elements of a vector space. The objective it tries to achieve is to minimize total intra-cluster variance, or, the squared error function. The k-means clustering was invented in 1956. The most common form of the algorithm uses an iterative refinement heuristic known as Lloyd's algorithm. Lloyd's algorithm starts by partitioning the input points into k initial sets, either at random or using some heuristic data. It then calculates the mean point, or centroid, of each set. It constructs a new partition by associating each point with the closest centroid. Then the centroids are recalculated for the new clusters, and algorithm repeated by alternate application of these two steps until convergence, which is obtained when the points no longer switch clusters (or alternatively centroids are no longer changed). Lloyd's algorithm and k-means are often used synonymously, but in reality Lloyd's algorithm is a heuristic for solving the k-means problem, as with certain combinations of starting points and centroids, Lloyd's algorithm can in fact converge to the wrong answer. Other variations exist, but Lloyd's algorithm has remained popular, because it converges extremely quickly in practice. In terms of performance the algorithm is not guaranteed to return a global optimum. The quality of the final solution depends largely on the initial set of clusters, and may, in practice, be much poorer than the global optimum. Since the algorithm is extremely fast, a common method is to run the algorithm several times and return the best clustering found. A drawback of the k-means algorithm is that the number of clusters k is an input parameter. An inappropriate choice of k may yield poor results. The algorithm also assumes that the variance is an appropriate measure of cluster scatter.

Histogram-based methods

Histogram-based methods are very efficient when compared to other image segmentation methods because they typically require only one pass through the pixels. In this technique, a histogram is computed from all of the pixels in the image, and the peaks and valleys in the histogram are used to locate the clusters in the image.[1] Color or intensity can be used as the measure.

A refinement of this technique is to recursively apply the histogram-seeking method to clusters in the image in order to divide them into smaller clusters. This is repeated with smaller and smaller clusters until no more clusters are formed.[1] [3]

One disadvantage of the histogram-seeking method is that it may be difficult to identify significant peaks and valleys in the image. In this technique of image classification distance metric and integrated region matching are familiar.

Histogram-based approaches can also be quickly adapted to occur over multiple frames, while maintaining their single pass efficiency. The histogram can be done in multiple fashions when multiple frames are considered. The same approach that is taken with one frame can be applied to multiple, and after the results are merged, peaks and valleys that were previously difficult to identify are more likely to be distinguishable. The histogram can also be applied on a per pixel basis where the information result are used to determine the most frequent color for the pixel location. This approach segments based on active objects and a static environment, resulting in a different type of segmentation useful in Video tracking.

Edge detection

Edge detection is a well-developed field on its own within image processing. Region boundaries and edges are closely related, since there is often a sharp adjustment in intensity at the region boundaries. Edge detection techniques have therefore been used as the base of another segmentation technique.

The edges identified by edge detection are often disconnected. To segment an object from an image however, one needs closed region boundaries.

Region growing methods

The first region growing method was the seeded region growing method. This method takes a set of seeds as input along with the image. The seeds mark each of the objects to be segmented. The regions are iteratively grown by comparing all unallocated neighbouring pixels to the regions. The difference between a pixel's intensity value and the region's mean, δ , is used as a measure of similarity. The pixel with the smallest difference measured this way is allocated to the respective region. This process continues until all pixels are allocated to a region.

Seeded region growing requires seeds as additional input. The segmentation results are dependent on the choice of seeds. Noise in the image can cause the seeds to be poorly placed. Unseeded region growing is a modified algorithm that doesn't require explicit seeds. It starts off with a single region A_1 – the pixel chosen here does not significantly influence final segmentation. At each iteration it considers the neighbouring pixels in the same way as seeded region growing. It differs from seeded region growing in that if the minimum δ is less than a predefined threshold T then it is added to the respective region A_j. If not, then the pixel is considered significantly different from all current regions A_i and a new region A_{n+1} is created with this pixel.

One variant of this technique, proposed by Haralick and Shapiro (1985),[1] is based on pixel intensities. The mean and scatter of the region and the intensity of the candidate pixel is used to compute a test statistic. If the test statistic is sufficiently small, the pixel is added to the region, and the region’s mean and scatter are recomputed. Otherwise, the pixel is rejected, and is used to form a new region.

Level set methods

Curve propagation is a popular technique in image analysis for object extraction, object tracking, stereo reconstruction, etc. The central idea behind such an approach is to evolve a curve towards the lowest potential of a cost function, where its definition reflects the task to be addressed and imposes certain smoothness constraints. Lagrangian techniques are based on parameterizing the contour according to some sampling strategy and then evolve each element according to image and internal terms. While such a technique can be very efficient, it suffers from various limitations like deciding on the sampling strategy, estimating the internal geometric properties of the curve, changing its topology, addressing problems in higher dimensions, etc.

The level set method was initially proposed to track moving interfaces by Osher and Sethian in 1988 and has spread across various imaging domains in the late nineties. It can be used to efficiently address the problem of curve/surface/etc. propagation in an implicit manner. The central idea is to represent the evolving contour using a signed function, where its zero level corresponds to the actual contour. Then, according to the motion equation of the contour, one can easily derive a similar flow for the implicit surface that when applied to the zero-level will reflect the propagation of the contour. The level set method encodes numerous advantages: it is implicit, parameter free, provides a direct way to estimate the geometric properties of the evolving structure, can change the topology and is intrinsic. Furthermore, they can be used to define an optimization framework as proposed by Zhao, Merriman and Osher in 1996. Therefore, one can conclude that it is a very convenient framework to address numerous applications of computer vision and medical image analysis.[4] Furthermore, research into various level set data structures has led to very efficient implementations of this method.

Graph partitioning methods

Graph partitioning methods can effectively be used for image segmentation. In these methods, the image is modeled as a weighted, undirected graph. Usually a pixel or a group of pixels are associated with nodes and edge weights define the (dis)similarity between the neighborhood pixels. The graph (image) is then partitioned according to a criterion designed to model "good" clusters. Each partition of the nodes (pixels) output from these algorithms are considered an object segment in the image. Some popular algorithms of this category are normalized cuts [5] , random walker [6] , minimum cut [7] , isoperimetric partitioning [8] and minimum spanning tree-based segmentation [9] .

Watershed transformation

The watershed transformation considers the gradient magnitude of an image as a topographic surface. Pixels having the highest gradient magnitude intensities (GMIs) correspond to watershed lines, which represent the region boundaries. Water placed on any pixel enclosed by a common watershed line flows downhill to a common local intensity minimum (LIM). Pixels draining to a common minimum form a catch basin, which represents a segment.

Model based segmentation

The central assumption of such an approach is that structures of interest/organs have a repetitive form of geometry. Therefore, one can seek for a probabilistic model towards explaining the variation of the shape of the organ and then when segmenting an image impose constraints using this model as prior. Such a task involves (i) registration of the training examples to a common pose, (ii) probabilistic representation of the variation of the registered samples, and (iii) statistical inference between the model and the image. State of the art methods in the literature for knowledge-based segmentation involve active shape and appearance models, active contours and deformable templates and level-set based methods.

Multi-scale segmentation

Image segmentations are computed at multiple scales in scale-space and sometimes propagated from coarse to fine scales; see scale-space segmentation.

Segmentation criteria can be arbitrarily complex and may take into account global as well as local criteria. A common requirement is that each region must be connected in some sense.

One-dimensional hierarchical signal segmentation

Witkin's seminal work[10] [11] in scale space included the notion that a one-dimensional signal could be unambiguously segmented into regions, with one scale parameter controlling the scale of segmentation.

A key observation is that the zero-crossings of the second derivatives (minima and maxima of the first derivative or slope) of multi-scale-smoothed versions of a signal form a nesting tree, which defines hierarchical relations between segments at different scales. Specifically, slope extrema at coarse scales can be traced back to corresponding features at fine scales. When a slope maximum and slope minimum annihilate each other at a larger scale, the three segments that they separated merge into one segment, thus defining the hierarchy of segments.

Image segmentation and primal sketch

There have been numerous research works in this area, out of which a few have now reached a state where they can be applied either with interactive manual intervention (usually with application to medical imaging) or fully automatically. The following is a brief overview of some of the main research ideas that current approaches are based upon.

The nesting structure that Witkin described is, however, specific for one-dimensional signals and does not trivially transfer to higher-dimensional images. Nevertheless, this general idea has inspired several other authors to investigate coarse-to-fine schemes for image segmentation. Koenderink[12] proposed to study how iso-intensity contours evolve over scales and this approach was investigated in more detail by Lifshitz and Pizer[13] . Unfortunately, however, the intensity of image features changes over scales, which implies that it is hard to trace coarse-scale image features to finer scales using iso-intensity information.

Lindeberg[14] [15] studied the problem of linking local extrema and saddle points over scales, and proposed an image representation called the scale-space primal sketch which makes explicit the relations between structures at different scales, and also makes explicit which image features are stable over large ranges of scale including locally appropriate scales for those. Bergholm proposed to detect edges at coarse scales in scale-space and then trace them back to finer scales with manual choice of both the coarse detection scale and the fine localization scale.

Gauch and Pizer[16] studied the complementary problem of ridges and valleys at multiple scales and developed a tool for interactive image segmentation based on multi-scale watersheds. The use of multi-scale watershed with application to the gradient map has also been investigated by Olsen and Nielsen[17] and been carried over to clinical use by Dam[18] Vincken et al.[19] proposed a hyperstack for defining probabilistic relations between image structures at different scales. The use of stable image structures over scales has been furthered by Ahuja[20] and his co-workers into a fully automated system.

More recently, these ideas for multi-scale image segmentation by linking image structures over scales have been picked up by Florack and Kuijper[21] . Bijaoui and Rué[22] associate structures detected in scale-space above a minimum noise threshold into an object tree which spans multiple scales and corresponds to a kind of feature in the original signal. Extracted features are accurately reconstructed using an iterative conjugate gradient matrix method.

Semi-automatic segmentation

In this kind of segmentation, the user outlines the region of interest with the mouse clicks and algorithms are applied so that the path that best fits the edge of the image is shown.

Techniques like Siox, Livewire, or Intelligent Scissors are used in this kind of segmentation.

Neural networks segmentation

Neural Network segmentation relies on processing small areas of an image using an artificial neural network [23] or a set of neural networks. After such processing the decision-making mechanism marks the areas of an image accordingly to the category recognized by the neural network. A type of network designed especially for this is the Kohonen map.

Pulse-Coupled Neural Networks (PCNNs) are neural models proposed by modeling a cat's visual cortex and developed for high-performance biomimetic image processing. In 1989, Eckhorn introduced a neural model to emulate the mechanism of cat's visual cortex. The Eckhorn model provided a simple and effective tool for studying small mammal's visual cortex, and was soon recognized as having significant application potential in image processing. In 1994, the Eckhorn model was adapted to be an image processing algorithm by Johnson, who termed this algorithm Pulse-Coupled Neural Network. Over the past decade, PCNNs have been utilized for a variety of image processing applications, including: image segmentation, feature generation, face extraction, motion detection, region growing, noise reduction, and so on. A PCNN is a two-dimensional neural network. Each neuron in the network corresponds to one pixel in an input image, receiving its corresponding pixel's color information (e.g. intensity) as an external stimulus. Each neuron also connects with its neighboring neurons, receiving local stimuli from them. The external and local stimuli are combined in an internal activation system, which accumulates the stimuli until it exceeds a dynamic threshold, resulting in a pulse output. Through iterative computation, PCNN neurons produce temporal series of pulse outputs. The temporal series of pulse outputs contain information of input images and can be utilized for various image processing applications, such as image segmentation and feature generation. Compared with conventional image processing means, PCNNs have several significant merits, including robustness against noise, independence of geometric variations in input patterns, capability of bridging minor intensity variations in input patterns, etc.

Open source software

Several open source software packages are available for performing image segmentation

- ITK - Insight Segmentation and Registration Toolkit (Open Source)
- ITK-SNAP is a GUI tool that combines manual and semi-automatic segmentation with level sets.
- GIMP which includes among other tools SIOX (see Simple Interactive Object Extraction)
- VXL
- ImageMagick
- 3DSlicer
- MITK [24] has a program module for manual segmentation
- OpenCV is a computer vision library originally developed by Intel.
- GRASS GIS has the program module i.smap [25] for image segmentation
- Fiji - Fiji is just ImageJ, an image processing package which includes different segmentation plug-ins.
- JavaScript Graph-based Segmentation [26] is a JavaScript implementation of the clustering technique described here [27].

There are also software packages available free of charge for academic purposes:

- GemIdent
- CVIPtools [28]
- MegaWave [29]

See also

- Computer Vision
- Data clustering
- Graph Theory
- Histograms
- Image-based meshing
- K-means algorithm
- Pulse-coupled networks
- Range image segmentation
- Region growing

External links

- Some sample code that performs basic segmentation [30], by Syed Zainudeen. University Technology of Malaysia.

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