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INTRODUCTION

Originally, the term lamp meant a shining object; one which shined of its own accord such as a torch. This came to mean any object that produces light by incandescent means (by glowing from heat). Today, it generally means any object that produces useful illumination. This paper considers all devices that produce light for illumination including incandescent and fluorescent lamps as well as lasers and light-emitting diodes (LEDs) as lamps in the broad generic sense.

In this whitepaper the term light is used in its broader interpretation. In the strict literal interpretation, light refers to the visible portion of the electromagnetic spectrum. However, the increasingly more common meaning of light is energy in that portion of the electromagnetic spectrum where its dual properties of a photon and a wave are useful. Under this definition, the spectrum of light covers mid infrared, from about 10 microns, up to but not including x-rays.

This whitepaper covers a number of different types of lamps. The kinds of lamps addressed in this report were chosen because they represent the ones most commonly encountered in machine vision. The coverage, by necessity, is generic. Within each lamp type, there are numerous variations. Each variation has special features that give it capabilities beyond the generic properties. For greater detail on options and special features, research manufacturers product literature. There are other lamps, not addressed in this paper, which may be useful, and should be considered for very special applications. For example, under lasers, this whitepaper describes only the semiconductor diode laser. There are many other lasers, and some of these other types have been applied to machine vision applications.

The attributes of each lamp can be plotted on a radar diagram as shown in Figure 1. This visual approach was introduced by Daryl Martin of Advanced Illumination.
Figure 1 – Radar Diagram for Lamp Attributes
FACTORS IN SELECTING LAMPS

In selecting a lamp there are factors to consider regarding the performance of the lamp, and there are other factors to consider in integration of the lamp into the system. The list below is a quick overview of these factors. This whitepaper provides more specific information on each lamp type in a later section.

LIGHT OUTPUT

Normally, the quantity of useable light is a primary concern. While generally speaking more is better, there can come a point at which the sheer magnitude of the light begins to degrade the system. Also, the characteristics of a lamp’s light is as important as its quantity.

Lamps designed for general illumination have their output rated in lumens. The quantity lumen is a statement of the total radiated visible power. This is the radiometric power, watts, corrected for the photometric response of the eye. That is:

\[ \Phi_{lm} = \int \Phi_W(\lambda) R(\lambda) \, d\lambda \]  

(1)

Where:

- \( \Phi_{lm} \) is the total light flux in lumens
- \( \Phi_W(\lambda) \) is the light flux in watts as a function of wavelength
- \( R(\lambda) \) is the photometric responsivity of the human eye

The photometric response of the human eye is given in Figure 2.

The lamp’s output flux at 555nm contributes fully to the lamp’s output in lumens; while its output at 455nm or 610nm contributes only 50% to the lamp’s output in lumens. Even though a lamp may have significant light output in wavelengths outside the visible spectrum, these wavelengths do not contribute at all to the lamp’s ratings in lumens.

Figure 2 – Spectral Response of the Human Eye
Specialized lamps, such as lasers or LEDs used for purposes other than generalized illumination, have their output rated differently. Lasers are usually rated in Watts (actually milliwatts). That is, the measurement is not spectrally weighted for the eye’s response.

LEDs, which were traditionally used for displays and indicators, are normally rated in candelas. A candela is a measurement of luminous intensity or the number of lumens emitted into one solid angle.

**EFFICIENCY**

In this time of careful consideration of every item’s environmental impact, efficiency of a lamp becomes an important consideration. Efficiency can be defined as the useful light energy output divided by the electrical energy required to produce the light.

**SPECTRAL CONTENT**

Every sensor has a responsivity that is a function of wavelength. Every object has reflection, transmission, and absorption that is a function of wavelength. The output signal from the sensor is the convolution over wavelength of the light source, the object, the sensor’s responsivity, and the effect of any other component (e.g. filter) in the optical path.

\[
S = \int \lambda I(\lambda) P(\lambda) O(\lambda) R(\lambda) d\lambda
\]

Where:

- \( S \) is the total system amplitude response
- \( I(\lambda) \) is the light source output as a function of wavelength
- \( P(\lambda) \) is the scene’s spectral characteristic
- \( O(\lambda) \) is the spectral characteristic of any part in the optical path such as a filter
- \( R(\lambda) \) is the spectral responsivity of the detector

The effectiveness of a quantity of light energy can only be adequately assessed when its spectral characteristics are known along with the characteristics of other optical components in the system.

**DIRECTIONALITY**

Another property of lamps is the directionality of the light; that is, the angular spread of light that reaches a point illuminated by the lamp. Direct light sources are those in which the angular spread of light reaching a point on an illuminated surface is very small. Direct light sources cast a strong shadow. Diffuse light sources are those that have an appreciable angular spread of light reaching a point on an illuminated surface. Diffuse light sources cast a diffuse or fuzzy shadow.
Direct sources can be made diffuse by the use of a diffuser inserted between the lamp and the area illuminated. It is impractical to make a diffuse source a direct source.

**HEAT GENERATION**

All light sources generate heat in addition to useful light. In some cases, the generated heat is very significant and its effects are an important element in a design. For other lamps, the heat generated is negligible under normal circumstances and can be ignored. Power sources for the lamps are another source of generated heat.

**TEMPERATURE EFFECTS**

Lamps, especially those that operate near room temperature, typically have a light output that is a function of ambient temperature. Lamps, such as incandescent lamps, which emit light through incandescence and therefore are very hot, have a light output affected very little by ambient temperature variations.

**SHORT TERM STABILITY**

Some lamps exhibit variations in light output over a short period of time. With these lamps, the effective illumination from one image to the next can vary significantly. Sometimes, these variations can be eliminated with the driving circuits.

**PERFORMANCE CHARACTERISTICS OVER TIME**

All light sources change over time. Generally, the light output decreases with lamp age. However, other characteristics such as the relative spectral content can also change.

**OPERATING LIFETIME**

Some lamps, like LEDs, have very long lifetimes and may never need replacing for the life of the vision systems. Some other lamps have relatively short lifetimes but have other characteristics that make them especially well-suited for certain applications. In vision systems using these lamps, provision must be made for frequent lamp replacement. The ratings for lamp lifetimes are usually available in catalogs and data sheets.

A suitable definition of "good lifetime" has three criteria:

- The costs of replacement lamps, labor, and equipment downtime is a very small fraction of a system’s operating costs
- End of live is not caused by catastrophic failure which results in increased repair labor and possible damage to other system components
- The end of live is predictable in both time and aging characteristics
Another important observation on lamp lifetime is the specified lifetime of a lamp is usually the point where half the lamps have ceased to operate or have a light output that is 70% of the lamp’s initial output.

**RELIABILITY/FAILURE MECHANISMS**
Each lamp has certain characteristic failure mechanisms. The system design can accentuate these mechanisms, lowering system reliability, or it can mitigate them and increase reliability.

**SAFETY AND ENVIRONMENT**
Some lamps are intrinsically safe and some have obvious, well known safety hazards. The source of electrical power for any lamp can be a safety hazard. Here are some general safety considerations for lamps:

1. For lamps with glass envelopes, use good safety procedures when handling the lamps. Keep them enclosed in a housing to protect workers and products in case of lamp breakage. Maintenance workers should wear gloves and face shields when relamping. Dispose of the lamp safely.

2. Many lamps are very hot when operating, and they remain very hot for a period of time after being turned off. Contact with any part of the lamp while hot can cause severe, painful burns. It is preferable to wait until the lamp has cooled before removing the lamp for replacement. If the lamp must be handled while still hot, provide insulating gloves for the worker replacing the lamp and a safe (nonflammable) container in which to place the hot lamp.

3. Consider all lamps as operating at dangerous voltages. Even LEDs, which operate with less than four volts across them, are often operated in series where the total voltage across the string of LEDs can become hazardous. The lamps should be enclosed to prevent accidental contact with the lamp, or with its wiring in case of breakage. Electrical interlocks are recommended to help prevent contact with dangerous voltages during relamping.

4. A number of different lamps use mercury or a phosphor. Both of these materials are toxic. Care must be taken to protect workers from exposure if the lamp breaks and also during relamping. Proper disposal of the lamps is necessary. For lamps containing mercury, most jurisdictions have regulations governing their disposal.

5. Most lamps that use an ionized gas, including mercury, xenon, and neon, generate ultraviolet (UV) light. Often the lamp envelopes are made from glass that absorbs most of the UV light. Some lamps are designed with envelopes to transmit the UV. There are hazards to eyes and skin from UV exposure. Also, UV radiation creates ozone, a very corrosive and toxic gas. Even the envelopes of “non-UV emitting lamps” may not absorb all the UV energy, especially the
longer UV wavelengths. There are no ready standards for safe UV exposure levels. Some organizations have provided guidelines for other purposes that give some recommendations to exposure.

6) In general, when using lamps that filter UV with their envelope, use a housing with a glass window (most glass absorbs most UV) to further reduce UV. The ozone produced by these lamps is not significant. When using lamps designed to produce UV, provide good shielding for workers’ safety and ventilation to remove the ozone.

7) In the U.S., the Bureau of Radiological Health regulates the classification of lasers and equipment using lasers and the conditions that must be met for the devices to be considered safe for use. Most other developed countries have similar laser classification and safety requirements. The standards are complex and designed to protect users from exposure to eyes and skin. Other light sources, as intense as lasers, are not necessarily covered by any regulations. It is up to the system designer to provide reasonable protection from exposure to these intense sources and to insure compliance with regulations.

8) While exposure to LED light is not regulated in the U.S., Europe and Japan do have regulations. Be sure to acquire and study these regulations when using LEDs for illumination.

**COST**

The price of a lamp ranges from a few pennies for small LEDs to hundreds of dollars for more specialized lamps. This is a factor in the cost of a vision system. However, picking the right lamp while giving little weight to its cost lowers engineering costs and potentially the cost other facets of the system.

**AVAILABILITY**

The availability of lamps ranges from off the shelf at the corner store to custom fabrication taking several months. Always give first consideration to using a stock lamp, especially one that is multiply sourced. However, do not overlook the possibility of using a custom lamp where it can contribute significantly to the application.
This section reviews the following lamp types:

- LED (light emitting diode)
- Xenon strobe
- Fluorescent
- Incandescent
- Halogen incandescent
- Laser diode
- HID
- Neon

**LIGHT-EMITTING DIODE**

The light-emitting diode (LED) is a semiconductor device. Current flowing through the diode junction elevates some electrons to an energy state higher than their rest state, but atomic forces act on these electrons to return them to their rest states. To return to their rest states, the electrons must shed the excess energy they gained from the electric current. In the material used for LEDs, a prevalent mechanism is for the electron to emit a photon as a means of dissipating the excess energy. The energy of the emitted photon, and therefore its color, is the difference in the electron’s energy between the higher energy state and the rest energy state.

An LED is physically a small piece of semiconductor material; the piece is called a die. In size, the die for a low-power LED is around one-half millimeter square and one-tenth millimeter thick (the size can vary from manufacturer to manufacturer and from product to product). For high-power LEDs the size of the die is much larger. The die is placed into a package. The most common package is a molded epoxy package, about 0.2 inches in diameter by 0.4 inches long. LED die are also placed into hermetic metal packages with glass windows or lenses for the light, as well as into brick type packages for surface mount.

The LED, as a single device, is a direct light source.
**Light Output**

The light output of a LED is typically measured as intensity. For visible LEDs, the unit or measurement is the candela, or sometimes the millicandela. A candela is one lumen into one steradian (the unit of solid angle). For infrared and ultraviolet LEDs, the unit of measurement is watts/steradian.

The measured intensity of a LED is a function of the lens in the package into which the LED is placed; the more focused the LED, the greater the intensity (although the total power out does not change with the lens used). A small, visible LED with no lens might have an intensity of around 4 mcd (millicandela). The same LED with a lens to create a narrow beam width could have a measured intensity of over 100 mcd.

For LEDs, efficiency is usually expressed as luminous efficacy (lumens/watt) for LEDs emitting visible light. This is also called “wall plug efficiency”. Note that two LEDs operating at different wavelengths likely have different luminous efficacy values because of the difference in wavelengths and not because one LED is more efficient at converting the electrons to photons. LEDs are approaching 150 lumens/watt luminous efficacy which is almost as good as very bright high-pressure sodium arc lamps.

**Spectral Content**

LEDs are available as white or color. Color LEDs have a principal wavelength with light energy falling off quickly away from this principal wavelength (narrow bandwidth). White LEDs are made from a blue LED with a phosphor coating to convert some of the blue light energy into green, yellow, and red wavelengths.

While not truly monochromatic, color LEDs are considered monochromatic because most of their light output is concentrated in a spectral band with a bandwidth between 40 and 160nm depending on the LED technology. The peak wavelength of a LED is dependent on the properties of the semiconductor material and its doping. LEDs are readily available in wavelengths from infrared (900nm) to blue (500nm). There are also LEDs at longer wavelengths (short wave IR) as well as ultraviolet.


Heat Generation

Because the efficiency of LEDs is modest at best, some of the electrical energy into a LED is dissipated as heat. Additionally, it is common to incorporate a resistor in series with a LED to act as a current supply. The total heat generated by one LED operating at 25 milliamperes with a series resistor off of a five-volt power supply is 125 milliwatts. This is not much power. LEDs are not considered to generate much heat for the light output.

In machine vision LEDs are usually operated in arrays with tens to hundreds of LEDs in the array. Total power dissipation for a 100 LED array could be around 12.5 watts. Application considerations, such as pulsed operation, can affect this heat generation.

Ambient Temperature Sensitivity

LED efficiency, and therefore the light output, decreases substantially with increasing temperature.

Short Term Stability

LEDs are very stable in the short term. Any short-term instability is likely to be in the power source.

Long Term Stability

The LED light output decreases very slowly over time. The rate of decrease is affected primarily by the operating temperature rise and by the current density at which the LEDs are operated.

Operating Life

Operating life is a function of the operating conditions. Typical ratings are either L70 or more rarely L50. L70 means the light output decreased to 70% of its initial value; L50 means the light output decreased to 50% of its initial value. Most typically, L70 values are used for machine vision. For sensitive applications, even a 30% decrease in light output may be unsatisfactory. A typical L70 value for LEDs used in machine vision is 50,000 hours. Lifetimes can be shorter or longer depending on operating conditions.

Figure 7 – Surface Mount LED
Figure 8 – Surface Mount LED
Figure 9 – Surface Mount LED
**Reliability/Failure Mechanisms**

The primary catastrophic failure mechanism is opening of the bonding wire to the LED much like a fuse opens when conducting excess current. This breakdown is accelerated by higher current operation. Operation within the limits of the device usually prevents the bonding wire from failing.

Junction degradation because of temperature cycling and high current density is a failure mechanism that causes the light output of the LED to diminish. Again, operation with recommended guidelines helps slow down this failure mechanism.

Overall, LEDs operating within the manufacturer’s limits are the longest lasting light source available.

**Safety**

There are no intrinsic safety hazards associated with LEDs. The voltage across any LED is low, usually under three volts for red LEDs and under five volts for blue LEDs. Depending on how LEDs are combined into arrays, the drive voltage can be high enough to present a hazard.

The light intensity of many LEDs is usually too low to provide any hazard associated with direct viewing when used alone. However, high-intensity LEDs have their light concentrated in a very narrow beam, and possibly pose a hazard to eyes if direct exposure is more than very brief. Also, arrays of LEDs may have intensity levels that are too great to be safe for normal direct viewing. People working with LED arrays, especially where the array is pulsed, usually advise against looking at the LED array directly. The European standard IEC 825-1 gives requirements for LED safety for use around people.

**Cost**

Plastic encased LEDs are available starting around $0.25 each. In a metal/glass package, LED prices start at around $2.00 each. Quantity discounts and special requirements such as highly focused LEDs or sorting for light output can affect the cost. Extremely high-power LEDs can cost close to $100.

**Availability**

Many varieties of LEDs are available directly from distributor stocks. Many additional varieties of LEDs are available from the manufacturer with a delay of 1 to 6 weeks depending on the product and special requirements. Special requirements that necessitate sorting and selecting or special packaging require even longer lead times.
Applications

In machine vision, LEDs have found their greatest use when ganged in arrays, either as a replacement for small fluorescent lamps operating continuously or as replacement for strobe lamps when pulsed for short durations. LED arrays are best used for imaging small to medium sized parts. Arrays of LEDs have been used successfully in backlights for bowl feeders, inspection of component leads through printed circuit boards, imaging packaging materials traveling on a conveyor line, inspecting PC boards, and reading semiconductor wafer ID marking.

Application Considerations

1. Color LEDs, being close to monochromatic, can be used where their wavelength is an asset or at least where their wavelength makes the desired features visible. For example, some PC boards image better under red LED light while other PC boards image better under green LED light. Where white light is needed, white LEDs can be used successfully.

2. Exploit the monochromaticity of LED light by using a matched filter over the camera lens. All ambient light, not at the narrow band of the LED light, is removed, and the signal-to-noise of the image is increased.

3. In the pulsed mode, LEDs can be driven at currents significantly above their continuous ratings; this is called overdrive. The limits are the average power dissipation and the peak current through the LED. The LED manufacturer can provide more information on the practical limits. Pulse times as short as 100 nanoseconds are possible. An array of LEDs is one option to a strobe lamp.

4. Study the degree of focusing (beam angle) of LEDs. Narrow beam LEDs are more efficient in delivering light to the field-of-view, but more difficult to aim and more likely to produce hot spots than are broader beam angle LEDs.

5. Drive LEDs from a circuit that provides as close to a constant current source as practical. This gives the best short-term stability. If the temperature varies more than 30 °F, consider adding some feedback to stabilize the light output. Insure that under no conditions, the maximum current level of the LED is exceeded.

Summary

Plotted on the radar diagram, LED attributes appear as shown in Figure 11.
Figure 11 – Attributes of Light Emitting Diodes
**XENON STROBE LAMP**

The strobe lamp, also called a flashlamp or capacitor discharge lamp, is a quartz or glass tube filled with pressurized xenon gas (or some other noble gas) with electrodes at each end. Gas pressure is typically between 400 and 700 torr (1 atmosphere of pressure = 760 torr). The shape of the tube may be straight, curved (in the shape of a "U"), or helical. The lamp is specifically designed to produce a very short high intensity burst of light energy.

A source of energy, usually a charged capacitor, is placed across the tube. The voltage on the capacitor (and the tube) is very high, but lower than required to initiate an electrical arc between the electrodes. A trigger current initiates a fine arc between the electrodes at each end of the tube. The electrical resistance of the lamp drops significantly, and the charge stored in the capacitor is discharged through the tube creating the gas plasma that produces the arc.

Often there is a fine wire wrapped around the tube. This wire serves as the ground reference for the gas in the tube, and can also be used for triggering.

There are two methods of triggering a strobe lamp. In external triggering, a very brief high voltage pulse is applied to the external wire grid around the lamp. This raises the voltage gradient within the gas (the gradient existing between the gas in the tube and the external wire grid) to a point where ionization, and therefore discharge, occurs. In series triggering, a high voltage pulse is coupled in series with the lamp power supply. This pulse voltage is higher than the lamp breakdown voltage and initiates discharge.

The strobe lamp is a direct light source.
Because LEDs can be pulsed on for very brief times and because they can be arranged in a wide variety of configurations and colors, LEDs have largely replaced strobe lamps in machine vision applications except where an extremely intense light is needed.

**Light Output**

In a typical strobe lamp, the light pulse lasts from 50 μsec to 2 msec. It is a function of the tube design, operating conditions, and the strobe power supply. Shorter pulse lengths, below 1 μsec are possible with special design.

Typically, strobe lamps are about 50% efficient when considering radiated light in the 200nm to 1,100 nm range. When considering the energy loss in the power supply, the overall efficiency is much lower. Smaller tube bores, especially below 2.5mm, tend to decrease efficiency rapidly. Xenon strobe lamps are more efficient than krypton lamps. Increasing the gas pressure or increasing the power density increases the efficiency somewhat. Shorter pulse times reduce overall efficiency.

**Spectral Content**

The spectral output of strobe lamps is a function of the power density at which they are operated. At low power densities, the lamp’s output has significant spectral peaks related to the gas’ electron energy level transitions. For xenon and krypton, these peaks are mainly in the near infrared region. However, at higher power densities, the gas plasma becomes incandescent, and the energy is whiter in content.

Interestingly, the spectral output of a strobe lamp varies during the light pulse. However, in most applications, the total light energy in the pulse is the important parameter. The integrated light output for most strobe lamps operated in the usual regions is reasonably white light.

Strobe lamps can produce significant amounts of ultraviolet. The envelope material has a significant bearing on the total amount, useful or unwanted, UV. Most strobe lamps are made with quartz (fused silica) envelopes. Quartz transmits near UV, but blocks far UV. Synthetic fused silica envelopes transmit more of the far UV. Glass, which effectively blocks most UV, can be used for envelopes. However, with its lower temperature tolerance, glass is not preferred for strobe lamps.

**Heat Generation**

Strobe lamps radiate very little far IR (heat) energy. However, the lamps themselves can become very hot during operation because of energy dissipation.
**Ambient Temperature Sensitivity**

Ambient temperature has very little effect on the output of a strobe lamp; typically no more than 5% change in light output.

**Short Term Stability**

Short term stability of the light from a strobe lamp is determined by the lamp's temperature, the stability (repeatability) of the energy pulse, and recovery time since the previous pulse. Pulse to pulse variations of light output from 10 to 20 percent have been reported in some situations. Typical variation is only 1 or 2 percent.

**Long Term Stability**

The light output of a strobe lamp may drop by around 15% during the first 100,000 flashes and is relatively stable after that. Decreases in lamp output with aging are not uniform over the spectra. UV output decreases the fastest. Visible output decreases faster than IR.

**Operating Life**

The lifetime of a strobe lamp is typically expressed in the total number of flashes it can produce before replacement is necessary. The principal determinants of lifetime are the energy per pulse and the pulse repetition rate. Lifetimes range from 20,000 to over 100,000,000 flashes. In machine vision, a lifetime of 10,000,000 is probably typical.

A way to estimate lifetime is as a function of the pulse energy relative to the explosion energy limit (see failure mechanisms below). A rough approximation for lifetime is:

\[
L = \left( \frac{E_o}{E_x} \right)^{-\beta}
\]

(3)

Where:

- \(L\) is the estimated lifetime in flashes
- \(E_o\) is the operating pulse energy
- \(E_x\) is the explosion energy limit
- \(\beta\) is an empirically derived constant, usually around 8.5 for lamps typically used in machine vision

For operating energy above 25% of the explosion energy, end of life is usually caused by catastrophic envelope failure. For operating energy below this level, failure is usually caused by other non-catastrophic mechanisms such as fill gas contamination.
Operating a lamp at 10% of explosion energy gives an estimated lifetime over 100 million flashes.

**Reliability/Failure Mechanisms**

During initiation of a pulse, there is a significant shock wave generated. This wave stresses the glass envelope. In addition, there are thermal stresses generated by the temperature gradients caused by the gas plasma. At some energy level, the stress causes the glass envelope to explode. The explosion energy limit is a function of the fill gas, the fill pressure, the shape of the energy pulse, the strength of the tube, and the effects of aging on the tube. Strobe lamps operated above the explosion energy limit can, and likely will, fail catastrophically.

Operating a strobe lamp for long pulse durations causes the anode to heat to a higher temperature than the same energy dissipated in a short pulse.

Failure of the seal between the electrode lead and the envelope is a major failure mode. Mechanical stress and certain operating modes accelerate this failure.

As the electrodes wear, a process called electrode sputter, the eroded material is deposited on the inside of the envelope. This decreases the light transmitted by the envelope – an effect most pronounced near the ends. Degradation of the cathode is more pronounced than the anode. The greater energy absorption in the darkened region causes increased thermal stress on the envelope that may eventually lead to envelope failure.

The fill gas may become contaminated. This usually results in difficult or erratic triggering.

**Safety**

Repetitive bursts of light energy at certain rates, especially at the alpha wave rate around 8Hz, can cause epileptic seizures.

Strobe lamps have an explosion limit, a pulse energy limit above which the lamp may explode. The actual explosion pulse energy limit decreases as the lamp ages. Strobe lamps should not be operated near or above the explosion limit.

**Cost**

Strobe lamps themselves can be very inexpensive, costing from $25.00 to $200.00 for standard lamps in small quantities. Lamps made to special order cost more depending on the design requirements.
Often the power source, trigger circuit, and lamp housing are much more expensive than the lamp. A complete strobe assembly typically costs from $1,500.00 to $5,000.00.

**Availability**

Although specialty distributors stock a few common strobe lamps, usually, standard lamps are available from stock at the manufacturer or are available on short lead times.

**Applications**

In machine vision, the principal uses are on high speed production lines where the short light pulse duration and very high light energy is needed to freeze the motion of parts in the image.

**Application Considerations**

1) Intense repetitious light bursts can be annoying to people. At certain critical repetition rates, the effect can cause epileptic seizures in some people. Ensure the light illuminating the scene is well shielded to avoid problems.

2) The strobe lamp operates at high voltages, typically in the neighborhood of 500 volts. Access to replace lamps must insure the service person does not come into contact with these voltages.

3) Also, in the case of externally triggered flash lamps, the wire grid around the lamp is pulsed to a very high voltage (in the thousands of volts). It is necessary to insure no person comes into contact with these wires while the lamp is operating. Since the lamp tube becomes hot during operation, unintentional contact with the tube should be prevented. Use of series triggering, where the wire grid is not present or is grounded, can further reduce the possibility of electrical shock.

4) Strobe lamps produce significant quantities of UV and IR energy. Normally the IR energy is not a safety problem. However, if the camera's sensitivity to near IR is not wanted, a filter is required. Most of the UV can be removed with a plain glass (not quartz or some other UV transmissive material) window.

5) External triggering, where the triggering voltage is applied to the wire grid around the lamp, gives a lower cost light source. Series triggering helps prevent exposed high voltage wires, is usually more reliable, and can produce lower EMI.
6) Strobe lamps are polarized; there is an anode and a cathode. Some lamps are made in such a way that the lamp cannot be replaced with the anode and cathode connected wrong. However, some lamps have the same terminals for the anode and cathode; usually one end has a marking. Make sure the relamping procedure insures the lamp is installed in the correct polarity.

7) Shorter arc lengths (shorter lamp tubes) can operate at shorter pulse durations.

8) The UV produced by strobe lamps, even if filtered out of the light incident on the scene, can produce ozone. Ozone is toxic and corrodes many materials including reflector surfaces. Ozone production is more pronounced as the wavelength of the UV becomes shorter. Selection of a strobe lamp with an envelope that filters out more of the shorter wavelength UV is desirable to limit ozone production.

9) Fingerprints on the envelope can lead to devitrification; a condition in which the envelope material changes structural form to an opaque form of SiO$_2$. Devitrification appears as a milky cloud in the envelope material. Not only does it reduce the light output, but it also significantly accelerates lamp failure.

10) Lamps should be handled only by the leads or with very clean gloves. If a lamp is touched with the finger, it should be cleaned before being operated. One cleaning procedure is a wipe-down with reagent grade acetone followed by a wipe-down with reagent grade isopropyl alcohol.

11) The lamp mount must be flexible to allow for thermal expansion of the lamp during operation.

12) Cooling the lamp increases its life. For lower energy applications where the average power density is below 10 watts/cm$^2$ of ID cross-section cooling makes much less difference. With proper air cooling, lamps can be operated at average power densities up to 30 watts/cm$^2$ depending on the effectiveness and uniformity of the cooling. It is possible, although uncommon in machine vision, to use liquid cooling and achieve power densities up to 200 watts/cm$^2$.

13) If the pulse repetition rate is high, pulse the lamp several times on start up before use. This brings the lamp up to operating temperatures and stabilizes its operation. If the repetition rate is extremely variable, forced air cooling helps stabilize light output.

**Summary**

Plotted on the radar diagram, xenon strobe lamp attributes appear as shown in Figure 15.
Figure 15 – Attributes of Xenon Strobe Lamps
**FLUORESCENT**

The fluorescent lamp is a glass tube with electrodes in each end. Ordinarily, the inside of the glass tube is coated with a phosphor. However, in fluorescent lamps designed to produce short wavelength UV, there is no phosphor coating. Depending on construction, the ends have electrodes or filaments. The glass tube can be straight, bent in the shape of a "U", or formed into a circle. Other shapes are possible.

The fluorescent lamp uses an ionized mercury gas. The ionized gas produces a great amount of ultraviolet and can be the direct radiator as in the case of a germicidal lamp where UV is desired. More commonly, the UV emission excites a phosphor that in turn, radiates light.

The fluorescent lamp is normally an almost omnidirectional diffuse radiator.

**Light Output**

The fluorescent lamp produces about 80 lumens/watt. Standard lamps produce about 800 lumens per foot of lamp length. Smaller diameter lamps produce less light/foot of lamp length. High output lamps are available that produce twice the light out per watt.

**Spectral Content**

Typically, some light energy from ionized mercury penetrates through the phosphor to provide the blue wavelengths, and the phosphor provides the green, yellow, and red wavelengths. The envelope effectively filters out the ultraviolet. The lamp’s light tends to be characterized by significant emission peaks and valleys; a “white” fluorescent lamp does not emit significant light at all wavelengths. The major differences in the various fluorescent lamps (e.g. “cool white” vs. “warm white”) are the difference in the phosphors and the locations of the spectral peaks.

**Heat Generation**

The lamp produces little heat and does not become hot during operation.
**Ambient Temperature Sensitivity**

Standard fluorescent lamp phosphors are designed for maximum efficiency at glass temperature of 105 °F. At temperatures above and below this, the efficiency of the phosphor decreases significantly. Over the ambient temperature extremes in a typical manufacturing plant, fluorescent lamp light output can vary by as much as 50% due to temperature changes.

In addition to the change in light output, there is a color shift with temperature. While the spectral peaks do not change in wavelength, as the phosphor efficiency falls, the contribution of its red light decreases while the mercury's blue light remains almost constant. The result is a shift in color temperature toward the blue.

**Short Term Stability**

When driven from the power lines, the fluorescent lamp flickers at twice the line frequency. Operated at 60Hz, the lamps flicker on and off 120 times per second. This flicker can be reduced by operating the lamp at a high frequency. Operated at 20 kHz, the flicker from a fluorescent lamp is only about 2% because of the persistence of the phosphor. For flicker-free operation, fluorescent lamps must be operated at a minimum of 20 kHz.

**Long Term Stability**

The lamp loses 10% to 15% of its light output during the first 200 hours and may lose another 10% before the end of its life. The principal mechanism is a loss in phosphor efficiency. As the phosphor ages and its contribution to light output decreases, there is a blue shift as described in temperature effects above.

Also, fluorescent lamps tend to darken at the ends due to evaporation of the filaments or electrodes onto the phosphor. The light at the ends falls off more quickly than the light over the center portion of the lamp.

**Operating Life**

Fluorescent lamps are rated for up to 20,000 hours of operation.

**Reliability/Failure Mechanisms**

The principal aging mechanism is phosphor aging.
Another common effect is the evaporation of the filaments/anodes. This is often seen as a blackening at the ends of the lamps. As the filaments/anodes evaporate, the lamp becomes harder to start and less efficient. Good connections to the lamp minimize the evaporation.

**Safety**

The major safety considerations are glass breakage, the toxicity of the phosphor and mercury gas, the operating and starting voltages, and possible emission of ultraviolet.

**Cost**

Standard lamps cost from as little as $2 to around $50. Custom lamps are available at reasonable prices.

**Availability**

Catalog lamps are usually available from distributor stock. Special fluorescent lamps are carried by only a few distributors nationally.

**Applications**

Fluorescent lamps commonly used when diffuse illumination over a large area is needed and color rendition is not a critical factor.

**Application Considerations**

1) Maintain good ventilation and cooling around the lamps. Light output is most stable when the glass temperature is maintained near 150 °f.
2) Use the highest quality socket possible to help prevent early failure.
3) Unless the camera is synchronized to the line frequency, use a high frequency ballast to prevent flicker and the resulting image artifacts.
4) Insist on relamping procedures that insure the lamp is replaced with one of the same phosphor characteristics (i.e. replace a "cool white" only with a "cool white" and not a "warm white").
5) Use a high-frequency ballast with a feedback sensor to help maintain long term stability.

**Summary**

Plotted on the radar diagram, fluorescent lamp attributes appear as shown in Figure 19.
Figure 19 – Attributes of Fluorescent Lamps
INCANDESCENT

In the past, incandescent lamps were the most common lamp in general (household) use. Because of their low efficiency, they are being phased out for general use, and replaced by quartz halogen, compact fluorescent, or LED lamps.

Incandescent lamps have tungsten filaments enclosed in a glass bulb. In size, they range from the small "grain-of-wheat" lamp, to large bulbs rated at 1000 watts. The bulb may be evacuated (i.e., a vacuum), or it may be filled with a noble gas such as krypton or xenon or, more commonly, a mixture of a noble and inert gas such as argon and nitrogen. The gas reduces the rate at which the tungsten evaporates and gives either longer life or more light from the same size bulb and filament.

In a common configuration, the bulb is a roughly round or tear-shaped bulb with a connector at one end. In this shape, the bulb radiates almost omnidirectionally. Another common configuration has a reflector as an integral part of the glass bulb. This form of light is more directional. Flood light versions having a beam angle of around 60 degrees; spot light versions have a beam angle between 10 and 20 degrees. In still another configuration, called a linear lamp, the bulb is a glass cylinder with a connector at either end. The filament is a long ribbon or coil of tungsten stretching from one end to the other.

Incandescent lamps are direct light sources. However, in some cases the bulb is frosted to provide a slightly more diffuse source. Linear incandescent lamps are somewhat diffuse.

Light Output
Incandescent lamps are known for high light output in relation to their size. Typically, they produce 20 to 40 lumens per watt of input power.

Efficiency
Incandescent lamps are considered among the least efficient of the general purpose light sources. This is why they are being replaced by more efficient quartz halogen, compact fluorescent, and LED lamps for general purpose lighting.
**Spectral Content**

Incandescent lamps produce a light that has enormous amounts of infrared energy, with the energy in the visible band being large in the red region and decreasing toward the blue region. The output spectrum is smooth and free of spectral peaks that characterize other types of lamps. Incandescent lamps do not produce useful amounts of ultraviolet light for two reasons: 1) there is little UV light produced at the temperatures where it is practical to operate the lamp filaments, and 2) the glass envelope is not transparent to UV. An incandescent lamp is an approximation of a black body radiator in the visible and infrared spectrum.

**Heat Generation**

Incandescent lamps are known for the heat they produce. Using any means to direct the light such as reflectors or lenses, increases the heat directed at the part being viewed. Optical components that can reduce the heat reaching the part are heat absorbing glass, a hot or cold mirror, and a dichroic reflector. Use of incandescent lamps increases the need for thermal considerations in the system design.

**Ambient Temperature Sensitivity**

The effects of ambient temperature variations are minimal. This is because the filament is operating so much above ambient temperature that the slight changes in filament temperature with ambient temperature changes are essentially negligible.

**Short Term Stability**

The light output of an incandescent lamp is dependent on the temperature of the filament and responds instantly to any change in filament temperature. The filament is fairly well thermally isolated from the environment within the bulb. Because of the thermal mass of the filament, the change in light output caused by the frequency of the power lines is small. However, in systems such as line-scan systems that operate asynchronously from the line, several percent ripple in light intensity can be detected. This ripple is eliminated when a DC power source is used.

**Long Term Stability**

The incandescent lamp is well known to have a light output that decreases significantly with time. This decrease is rather rapid during the first hours of operation, and then slows down until the lamp is near the end of its life. The principal mechanism is that the tungsten slowly evaporates from the
hot filament and redeposits on the inside of the glass bulb. The evaporated tungsten is dark and attenuates the light. The use of a noble fill gas reduces the rate of tungsten evaporation.

Systems that use incandescent lamps need either to be constantly adjusted, or have a high tolerance to light level variation to handle the declining light output.

**Operating Life**
Standard household incandescent bulbs are rated for 1000 hours of operation at rated voltage. Operating an incandescent lamp at a lower voltage significantly extends the life of the bulb, but with reduced light output and a shift in the light spectrum. As a general rule in the vicinity of its rated voltage, the lifetime and light output follow these relationships:

\[
L_E = L_R \left(\frac{V_A}{V_R}\right)^{12} \tag{4}
\]

And

\[
I_E = \left(\frac{V_A}{V_R}\right)^{2.6} \tag{5}
\]

Where:

- \(L_E\) is the expected lifetime of the lamp
- \(L_R\) is the rated lifetime of the lamp
- \(I_E\) is the expected light output
- \(I_R\) is the rated light output
- \(V_A\) is the applied voltage
- \(V_R\) is the rated voltage

Decreasing the voltage by 4.6% increases the life of the bulb by 100%, but decrease the light output by 14%. Using lamps of higher power ratings at derated voltages is one way to significantly improve system reliability.

**Reliability/Failure Mechanisms**
The principal failure mechanism in a incandescent is catastrophic filament breakage. There are several factors that contribute toward this failure:

- Thinning of the filament through evaporation
- Breakage of the filament because of shock or vibration, both thermal and mechanical
- Migration of the tungsten with the current flow
The thinning of the filament through evaporation is a natural effect, and the only technique to reduce the thinning rate is to lower the operating voltage. The thermal shock from turning the lamp on is known to decrease the life of the lamp. Data on the magnitude of this effect is, however, somewhat sketchy. A good general rule of thumb is to leave the lamp on if the system is to be used again within 24 hours.

A hot filament is much weaker mechanically than one at room temperature. Shock and vibration do far more damage in weakening the filament when the lamp is operating. Some approaches to help are:

- Isolate the lamp from shock and vibration
- Select a low voltage lamp with a shorter, thicker filament
- Avoid lamps with long filaments
- Select a lamp that has filament supports

A low voltage lamp has a shorter, thicker filament than a lamp of the same wattage designed for higher voltages. For the same wattage and light output, the filaments in low voltage lamps are inherently more rugged than higher voltage lamps. Some incandescent lamps, especially those of the tubular design, have long slender filaments. These are well known for being susceptible to failure with even low levels of shock or vibration. There are lamps designed for application in rugged environments. Often, these lamps incorporate supports at points along the length of the filament.

An interesting effect in metals is the physical migration of metal molecules in the direction of current flow. The magnitude of the migration is a function of the current density; the higher the current density (amps/cm²) the greater the rate of migration. When lamps are operated from alternating current, there is the effect of reversing the migration every time the current reverses. With direct current operation, the migration effect is much more pronounced. Although a filament is nominally a uniform diameter, there are slight variations along its length. Migration is greater at the thinner cross sections. The thinner spots continue to become thinner. Examination of lamps operated from DC show pronounced notching or localized thinning because of migration.

Lamps operate longer with AC operation. In those circumstances where it is desirable to operate the lamp from DC, one alternative is to switch the current flow to the lamp from time to time. However, experience shows this task is not performed reliably. Usually, the system must be designed to accommodate the reduced lifetime of the lamp.

**Safety**

The safety considerations for incandescent lamps are: glass breakage, heat, and high voltage.
The heat produced by the lamps must be dissipated. Some of the heat is projected along with the light onto the scene. There have been machine vision systems in which the projected heat from the incandescent lamp was sufficient to cause burns in only a second to a person’s hand placed in the field-of-view. Typically, the housing around the lamp gets very hot unless substantial ventilation is provided.

**Cost**
The incandescent lamp is one of the least expensive lamps. A typical household lamp costs around a dollar, but is becoming more difficult to find. Specialty lamps can range from a few to several hundred dollars.

**Availability**
Standard, incandescent household lamps are becoming more difficult to find. They are not recommended for new designs. Specialty incandescent lamps should remain available for quite a while through distributors and can be considered for designs.

**Application**
The incandescent lamp is useful where a low-cost source of direct light is desired and shorter lifetime and significant heat can be accepted. The application must be able to tolerate the slowly but continuously declining light output. Incandescent lamps are rare for use in machine vision applications.

**Application Considerations**
- Use a hot mirror or heat absorbing glass in the optical path to prevent heat from reaching the field-of-view. The heat reflected from a hot mirror must be dissipated by some means. Heat absorbing glass needs a thermally conductive path through which to dissipate the heat, and careful consideration of the effects of thermal expansion.
- For lamps under 5 watts, usually no special cooling considerations are required unless the lamp housing is very compact. For lamps up to 50 watts, convection cooling is usually sufficient. Lamps over 50 watts often need forced air cooling.
- Use the lowest voltage lamp available with the other necessary properties. This requires a step-down transformer that adds slightly to the system cost.
- Use an operating voltage below the rated voltage to extend the lamp’s lifetime.
- If ripple in the image (e.g. with line-scan cameras) is a problem use a DC source. Using DC may reduce the lamp’s lifetime.
Summary

Plotted on the radar diagram, incandescent lamp attributes appear as shown in Figure 23.

![Incandescent Lamp Attributes](image)

Figure 23 – Incandescent Lamp Attributes
HALOGEN INCANDESCENT
This bulb is also called quartz halogen when the envelope is made from quartz instead of glass. Like the common incandescent lamp, the halogen incandescent lamp is a direct light source that uses a tungsten filament inside a bulb. However, the bulb, usually quartz or Pyrex to withstand the high temperature, is filled with a halogen gas (e.g., iodine or bromine) under pressure. When the halogen gas is hot, it has the effect of removing any tungsten evaporated on the bulb and redepositing it on the filament. This process is called gettering.

To be effective, the halogen gas must be under several atmospheres of pressure and must reach a minimum temperature of 700 °f. The bulb is smaller than that of a normal incandescent to be nearer the filament for better heat transfer.

The lamps are available in ratings of a few watts up to 1000 watts. The filaments are usually operated at a higher temperature than the common incandescent lamps. This gives a much "whiter" light.

One of the more common applications for halogen lamps is in projectors. However, they are also finding wide application in retail display and automotive lamps. Often the lamps are available with the bulb mounted in a reflector. Unlike the common incandescent lamp, the reflector is not integral with the bulb.

Light Output
Because of the higher filament temperature and smaller envelope size, halogen lamps produce more light than comparable common incandescent lamps. They can produce about 60 or more lumens/watt.

Spectral Content
The halogen lamp has significant infrared energy. In the visible spectrum, its light covers the range from red through blue with the most energy in the red region, and decreasing steadily into the blues. When used with a quartz envelope, the halogen lamp does produce some near ultraviolet light. However, it is so energy inefficient at producing ultraviolet, it is not a suitable UV source. Still, there are long-term exposure concerns for people working around halogen lighting.
Heat Generation
Halogen lamps are known for the heat they produce. Using any means to direct the light such as reflectors or lenses, increases the heat directed at the part being viewed. Optical components that can reduce the heat reaching the part are heat absorbing glass, a hot or cold mirror, and a dichroic reflector. Use of a halogen incandescent lamp increases the need for thermal considerations in the system design.

Ambient Temperature Sensitivity
The effects of ambient temperature variations are minimal. This is because the filament is operating so much above ambient temperature that the slight changes in filament temperature with ambient temperature changes are essentially negligible.

Short Term Stability
The light output of a halogen lamp is dependent on the filament temperature and responds instantly to any change in filament temperature. Because of the thermal mass of the filament, the change in light output due to the frequency of the power lines is small. However, in systems such as line-scan systems that operate asynchronously from the line, several percent ripple in light intensity can be detected. This ripple is eliminated when a DC power source is used.

Long Term Stability
Because of the gettering of the halogen gas, the halogen incandescent lamp has a much more constant light output over its useful life than the standard incandescent lamp. After a short initial period in which light could decrease by 10%, the light output is constant within 90% for the balance of the lamp’s life.

Operating Life
Halogen lamps designed for projectors have a rated life from 20 to 200 hours. There are halogen lamps made for other applications that have lifetimes in the 1,000 to 2,000 hour range.

Similar to common incandescent lamps, reducing the operating voltage can extend lifetime. However, if the voltage is reduced too low, the envelope is not heated sufficiently to maintain the halogen cycle; the bulb’s lifetime is reduced, and the light output is no longer constant. Generally, operating the bulb below 70% of its rated voltage is too low for the halogen cycle to work. Some derating, up to 15% or 20% is very beneficial to increasing lifetime.
**Reliability/Failure Mechanisms**

All the reliability and failure mechanisms for normal incandescent lamps apply to halogen incandescent lamps.

Because of the high envelope temperature and high internal pressure, halogen bulbs are prone to catastrophic failure (explosion) if the envelope is damaged. Even the slightest abrasion or chip on the envelope cannot be tolerated.

Another precaution is never to touch the envelope with bare hands. It must be handled only by the base, or if the bulb must be handled, by using an oil free cloth or other suitable material. Skin oils are slightly corrosive to glass and quartz. Over time, the etching effect of skin oil causes stresses in the envelope leading to catastrophic failure. If a bulb is touched, it should be carefully cleaned with alcohol to remove the skin oils before it is used.

**Safety**

As with common incandescent lamps, the safety considerations are the glass envelope, the heat generated, and the voltage.

However, the high envelope temperature of the bulb makes the replacement of lamps a job that should only be performed by trained personnel. Contact with the bulb of a hot halogen lamp can cause very severe burns.

Because of the high internal pressure of the halogen gas, there is the possibility of the lamp exploding. There should be protection against flying glass if the envelope breaks.

**Cost**

A typical quartz halogen projector bulb costs around $30. Other versions cost from ten to several hundred dollars for the higher powered lamps.

**Availability**

Most halogen bulbs are available from a distributor's stock. Some bulbs of older designs or which were designed for a specialty market are harder to obtain.

**Applications**

The halogen incandescent lamp can be used anywhere an economical intense source of light is desired.
Application Considerations

- Use a hot mirror or heat absorbing glass in the optical path to prevent heat from reaching the field-of-view. The heat reflected from a hot mirror must be dissipated by some means. Heat absorbing glass needs a thermally conductive path through which to dissipate the heat, and careful consideration of the effects of thermal expansion.

- For lamps under 5 watts, usually no special cooling considerations are required unless the lamp housing is very compact. For lamps up to 50 watts, convection cooling is usually sufficient. Lamps over 50 watts usually need forced air cooling.

- Use the lowest voltage lamp available with the other necessary properties. This usually requires a step-down transformer that adds slightly to the system cost. However, the increase in reliability of the design more than offsets the cost of the transformer.

- Use an operating voltage below the rated voltage to extend the lamp’s lifetime. However, to preserve the halogen do not go below 80% of rated voltage without careful research and evaluation.

- If ripple in the image (e.g., with line-scan cameras) is a problem use a DC source. Using DC reduces the lamp’s lifetime.

- Provide adequate shielding against injury to people or parts if a bulb explodes.

- Provide for safe lamp replacement. When rapid lamp changeover is necessary, have redundant lamps where a second lamp can be used while the failed lamp cools off (some of the better projectors have this feature), use sockets with built-in extraction levers so the operator does not need to touch the bulb, and provide thorough training in lamp replacement.

Summary

Plotted on the radar diagram, incandescent lamp attributes appear as shown in Figure 28.
Figure 28 – Halogen Incandescent Lamp Attributes
**SEMICONDUCTOR LASER**

The semiconductor diode laser is a PN diode that both generates and amplifies light. At low drive currents, it generates and emits light just as a LED does. At higher drive currents, lasing action (amplification) begins. The diode laser is usually small, about the same size as an ordinary power transistor. It is a direct light source.

The laser diode is often packaged with beam forming optics, and the overall size with simple optics, not including power supply, can be around 0.5 inch diameter by 1 inch long. The power supply may be small (a small laser diode can easily be battery powered like a flashlight). Most laser diodes used in machine vision have sophisticated power supplies designed to regulate the light output or provide high pulse energy. These power supplies are usually larger than the assembly of the laser diode and optics.

Controlling the current that flows through the diode laser can modulate its light output. One way this is used is to feedback the signal from a sensor to maintain constant light output. Another use is to pulse the laser similarly to a strobe.

Diode lasers are available in different constructions. Among them are single-mode, multi-mode, multi-striped, and wide-channel. Single-mode and multi-mode laser diodes usually have power outputs in the range of 1 to 100 mw. Multi-striped and wide-channel diode lasers can have powers up to 1 watt.

**Light Output**

Diode lasers are available to produce from 1 milliwatt to 3 watts of continuous light power. Pulsed power outputs can reach peaks of several hundred watts.

For a gain guided diode laser, the lower cost and more traditional laser diode, the beam is not symmetrical (round); it is elliptical. Typically, its divergence is three times greater in one direction (across the beam) than in the other. This is called astigmatism. The divergence angle out of the laser diode, before any optics, is in the range of 10 to 60 degrees.

Index guided laser diodes have very little astigmatism, and are easier to collimate and focus to a point. The laser diode's light output has a preferred direction of plane polarization. However, the polarization ratio is usually better than 10, but rarely better than 100, and changes with power levels.
The laser diodes themselves are about 30% energy efficient. However, when the efficiency of the power supply and the energy used to provide cooling, the overall efficiency is very low.

**Spectral Content**

Output wavelengths from 1,500nm (short wave IR) through 405nm (violet) are available. The output is typically very monochromatic with a spectral width of 2 to 3nm. The diode laser has much less spatial coherence than other types of lasers; this is even more true for multi-mode lasers than for single-mode lasers. The result of the reduced spatial coherence is a reduction in speckle. Speckle is a noise component in most laser-based machine vision systems caused by interference of the laser light with itself.

**Heat Generation**

The laser diodes dissipate only about 0.1 to 5 watts of power. There is no heat energy in the light output.

**Ambient Temperature Sensitivity**

The laser diode’s power output is extremely temperature dependent. Also, wavelength is temperature dependent, varying about 0.25 nm/°C.

**Short Term Stability**

With feedback control, the light out of the laser can be stable to 0.1%. Because the laser resonance cavity is in a monolithic structure, the optical power does not vary with mechanical vibration.

**Long Term Stability**

The efficiency of a laser diode decreases with time. Because the devices are usually operated with feedback to provide constant power, the operating effect is an increase in drive current to maintain power output. The end-of-life occurs when the drive current reaches 130% to 150% of its initial value.

**Operating Life**

The operating life is typically between 30,000 to 100,000 hours depending on power level and operating temperatures. Operating temperatures much above room temperature drastically shorten the diodes lifetime. The lifetime decreases by about half for every 7 °C rise in diode temperature.
Reliability/Failure Mechanisms

Laser diodes have proven to be very sensitive to electrical transients such as voltage or current spikes from the power supply or electrostatic discharge during handling. Ninety percent of the catastrophic failures of laser diodes are caused by either electrostatic discharge or power supply related causes.

Operating at temperatures (measured at the device) of over 40 °C, causes extremely rapid degradation.

Safety

All equipment using lasers in the U.S. comes under the regulations of the Bureau of Radiological Health. Other developed countries have their own regulations. Depending on the wavelength and output power levels, the laser is assigned to a class. Different classes of lasers have different safety requirements. When considering a system using a laser, check for the latest regulations. Using a certified laser does not make the system employing the laser certified, nor does it imply the system meets the requirements of the regulation. Obtaining certification is time consuming and costly.

The major safety consideration for lasers used in machine vision is potential damage to eyes.

Cost

A low power laser diode, 10 mw output or less, costs from $2 to $200. A high power laser diode, with powers between 100 mw to 10 w, costs $900 to $10,000 or more. In addition, a power supply costing between $1,000 and $5,000 is required.

Availability

Most laser diodes are available from distributor’s stock or shipped from the factory with a 2 to 12 week lead time.

Applications

Typical applications include structured light illuminators, laser scanners, and LIDAR (laser radar) imaging. Structured light illuminators project a single line, a group of parallel lines, an array of dots, or other user defined patterns.
Application Considerations

1. There are many successful installations using lasers that have not been evaluated to determine they meet requirements for certification. However, it is unwise as well as illegal to install or cause a system to be operated that is not certified. Careful attention to all safety considerations is necessary.

2. Unless the laser must be focused to the smallest possible spot, use a multi-mode laser in preference to a single-mode laser to reduce speckle and the image noise it causes.

3. Use a matched narrow-pass filter over the detector/camera to reduce the effects of ambient illumination and enhance the signal-to-noise of the image.

4. Insure there is good heat sinking between the diode and the ambient environment. Otherwise, the diode’s operating temperature will be excessive and radically diminish the laser diode’s lifetime.

5. When handling the laser diode, use proper precautions to prevent damage from electrostatic discharge.

6. Because power out, wavelength, and lifetime are all very temperature dependent, use a regulated cooling system if possible. Thermoelectric coolers are often used with laser diodes. Temperature regulation targets should be around 1 °C.

7. Insure the power supply is free of any overshoot, undershoot, or transients. Use the softest turn-on and turn-off if practical.

Summary

Plotted on the radar diagram, incandescent lamp attributes appear as shown in Figure 30.
Figure 30 – Laser Diode Attributes
HIGH-INTENSITY DISCHARGE (HID) LAMP

The high-intensity discharge lamp uses an arc tube containing electrodes and filled with a gas or metal salt. The arc tube is contained within a glass envelope. The voltage applied to the lamp causes plasma to form using the gas or vaporized metal salt as the medium.

The HID lamp category includes mercury vapor, high pressure sodium vapor, and metal halide lamps. The principal difference in the various HID lamps are their spectral outputs. Other differences are in the voltages required and the lamps’ lifetimes.

Mercury vapor lamps use a quartz arc tube filled with argon gas and a small amount of mercury. High pressure sodium lamps use a transparent ceramic arc tube filled with xenon or mixture of neon and argon gas as well as sodium and mercury. Metal halide lamps use a quartz arc tube filled with argon gas, some mercury, and a metal halide salt. Common metal halide salts are sodium iodide, scandium iodide, thallium iodide, indium iodide, iron iodide, and gallium iodide.

HID lamps are omnidirectional radiating, direct light sources.

Light Output

Mercury vapor lamps are available in power ratings between 50 and 1,000 Watts with light output ranging between 1,260 to 50,000 lumens. So, mercury vapor lamps produce between 25 and 50 lumens per Watt.

High pressure sodium lamps are available in power ratings from 35 to 1,000 Watts, and produce between 2,050 to 120,700 lumens. Their efficiency ranges from 59 to 121 lumens per Watt.

Metal halide lamps have input powers from 35 to 2,000 Watts, and provide between 1,820 and 170,000 lumens. Their efficiency ranges from 52 to 85 lumens per Watt.
Spectral Content

Mercury vapor lamps generate a blue-white light output that has a large quantity of UV. The lamp produces strong spectral peaks in the yellow and green region with virtually no red. The lamps can be constructed with envelope materials that either transmit or absorb the UV. In some lamps the glass envelope is coated with a phosphor that absorbs the UV and reradiates it as visible light.

High pressure sodium lamps provide all their light distributed in the 550 to 700 nm region. There is a strong peak at 575 nm, and a notch at 590 nm. The light also contains a very small amount of the mercury spectrum.

Metal halide lamps are noted for a very white appearing light. However, the light does have numerous spectral peaks that depend on the specific metal-halide compound used. For example, when the metal-halide compound is iron iodide, the lamp has a strong spectral peak at 380nm. When the metal-halide compound is gallium iodide, there are spectral peaks around 403 and 417nm.

Heat Generation

HID lamps radiate little far-IR (heat). However, the lamps themselves become very hot during operation.

Ambient Temperature Sensitivity

Within ambient temperature variations encountered in the factory, because the arc is very hot, the lamps’ spectrum and light output are unaffected.

Short Term Stability

These lamps are very stable when operated at rated power. When operated below rated power, there can be some variation in light output.

Long Term Stability

For mercury vapor lamps there is no shift in the spectral peaks because of aging or power changes. The quartz tube, however, devitrifies as it ages, and its spectral transmissivity changes. Thus, the relative power in the peaks changes with lamp age.

The light output of high pressure sodium lamps decreases by 20% over the rated life of the lamp. There is no spectral change with time.
Metal halide lamps have their light output decrease 20% to 25% over their lifetime. There may be a slight shift in overall color appearance, but not the wavelengths of the spectral peaks, during the first few hundred hours of the lamp's life.

Operating Life
Lifetime for mercury vapor lamps can be as short as 500 hours for some very high output lamps, but are more commonly around 10,000 to 24,000 hours. High pressure sodium lamps have lifetimes around 24,000 hours. Metal halide lamps have rated lifetimes in the 3,000 to 10,000 hour range.

Reliability/Failure Mechanisms
The principal degradation in the lamp is the devitrification of the quartz tube. There is also evaporation of the tungsten electrodes onto the inside of the tube, as well as leaks at the electrode to tube and lead to envelope seals.

Safety
Because the gas in the arc tube is operating under a pressure around 10 atmospheres, there is the possibility of lamp explosion. An HID lamp turned on and never turned off might likely explode at its end of life. However, turning the lamp off periodically, and restarting it eliminates the most risk of explosion. As the lamp ages and the electrodes wear, the lamp becomes harder to start. Normally, the lamp fails to start before it is likely to explode.

Although HID lamps operate at moderate voltages in the range of 45 to 100 volts, their starting voltages are high; from as little as 1,000 volts to as much as 30,000 volts. The quartz arc tube runs extremely hot, and contains mercury that is toxic. The glass bulb containing the arc tube can get very hot; up to 800 degrees for some lamps.

Cost
Mercury vapor lamps typically cost between $30 and $100. Typical prices for standard high-pressure sodium lamps are around $45. Metal halide lamps cost between $12 and $50.

These priced do not include the housing and ballast. These additional items can add a few hundred to several thousand dollars.

Availability
Most lamps are available stock from distributors.
Applications

Mercury vapor and high pressure sodium lamps are suited for color grading where their spectral peaks are useful. High pressure sodium lamps are also suitable for applications that are not spectrally sensitive but require the maximum possible light power. Metal halide lamps are suitable for applications which require a very intense, efficient, and long-lasting source of white light.

Application Considerations

1. There are usually restrictions on the burning position of the lamp.

2. Because of the strong spectral character of light from mercury vapor and high-pressure sodium lamps, insure there is spectral compatibility, creating image contrast, between the lamp’s output and the object being viewed.

3. HID lamps require a minimum warm-up period of three to twenty minutes to achieve stability. Some metal halide lamps can reach 80% of output in twenty seconds.

4. For re-ignition, the lamp must cool down after being turned off. A minimum period of several minutes is needed before re-ignition can take place. After that, there is an additional period of time to achieve stability of light output. Because of work done for automotive headlamps, some metal halide lamps with their associated ballasts can be restarted very shortly after being turned off.

5. Insure correct handling and disposal procedures are followed during relamping and maintenance to avoid the problem of mercury contamination.

6. Turning off an HID lamp during its run-up time can severely shorten its life.

7. The lamp and ballast must be matched. It is not safe to use a HID lamp on a ballast not recommended for the specific lamp.

Summary

Plotted on the radar diagram, HID lamp attributes appear as shown in Figure 33.
Figure 33 – HID Lamp Attributes
**NEON**

A neon lamp is a glass tube with electrodes at both ends. The tube is filled with a gass and usually has a phosphor coating on the inside. Neon gas alone gives an orange-red color. Neon with a phosphor can produce orange and pink colors. If the tube is filled with a mix of argon and mercury vapor, it glows a light blue color. Other phosphors produce a variety of colors from the UV light emitted by the mercury.

The neon lamp is a diffuse light source.

**Light Output**

Neon lamps are most suited for displays, their light output and efficiency is much lower than lamps designed for illumination.

**Spectral Content**

The light output has spectral peaks depending on the gasses and phosphors used. Most neon lamps are a rough approximation to a monochromatic light. The exception is white, which is similar to a fluorescent in that it has a broader spectrum made up of emission peaks characteristic of the phosphor.

**Heat Generation**

Neon lamps produce virtually no heat.

**Ambient Temperature Sensitivity**

Technical information on temperature effects is not available. Because the quality control is so variable, it is hard to be certain of quantifying these effects.

**Short Term Stability**

When driven from the power lines, neon lamps flicker at twice the line frequency. Driving them from high frequency sources is very difficult, but has been done.

**Long Term Stability**

Technical information on long term performance is not available. Phosphors are known to degrade with time, and the light output from neon lamps using phosphors will decrease with time. However, because small local suppliers fabricate the lamps, quality control procedures are non-existent, and actual predictions are difficult.
Operating Life
No technical information on operating life is available. Neon signs are known to last for years. However, the lack of quality control in the fabrication of the lamps makes predictions difficult.

Reliability/Failure Mechanisms
The principal failure mechanism is the gas leakage out of the tube. Electrode erosion is also a factor.

Safety
Major hazards are glass breakage and the toxicity of phosphors and the mercury vapor, if used. Neon lamps operate with starting voltages as high as 15,000 volts; presenting a very real electrical shock hazard.

Cost
A simple lamp might cost $100 to have fabricated. The cost increases less than proportionally as the length and complexity of the lamp increases.

Availability
Neon lamps are custom fabricated, usually by a local supplier.

Applications
Use neon lamps where a very custom diffuse lamp is required.

Application Considerations
1) Because the businesses that produce the neon lamps are typically oriented to displays, there is little quality control over factors that can be important in technical applications. Those factors are the gas mixture and fill pressure, and the supplier and composition of the phosphor coated tube. Neon lamp manufacturers are accustomed to hand fabricating lamps to a paper template or drawing; do not expect high precision work.

Summary
Plotted on the radar diagram, HID lamp attributes appear as shown in Figure 35.
Figure 35 – Neon Lamp Attributes
SUMMARY

The figure below, Figure 36, compares the attributes of the lamps covered in this paper.
CONCLUSION

There is a wide array of lamps for machine vision applications. LEDs dominate for machine vision applications. Incandescent, halogen incandescent, fluorescent, and xenon strobe lamps will continue to be used when their special characteristics are needed. Laser diodes, HID lamps, and neon lamps serve occasional unique application requirements.

Perhaps too little has been done to inform people of the safety aspects of the different lamps. Fortunately, there are no reports that create any cause for alarm in this respect for machine vision. Today, though, the climate requires all of us to use the best available information in designing equipment and its operating procedures. Hopefully, the information contained in this paper helps.

Finally, the concept of lamp life is often regulated to the "if it ain't broke, don't fix it" procedure. However, this is probably not the most economical approach. Good systems engineering is needed to determine the economical point considering lamp cost, labor cost, disruption to production, and degradation of system reliability as the lamp ages.
**appENDIX A – GLOSSARY**

**astigmatism** – For a laser, a condition where the divergence of the beam is different for the vertical and horizontal cross sections of the beam. The result is an elliptical spot rather than a circular spot.

**bulb** – The glass housing of a lamp.

**candela** – The unit of luminous intensity equal to one sixtieth (1/60) the luminous flux of a one square centimeter blackbody at the solidification temperature of platinum. Approximately equal to the amount of light generated by one candle. Abbreviated cd.

**die** – A semiconductor device such as a transistor, diode, or integrated circuit not including the package. More specifically, a portion of a silicon wafer containing one semiconductor device which has not been placed in a package.

**diode laser** – Also solid-state laser and semiconductor laser. A laser that is a P-N semiconductor junction constructed to create a cavity in which light emitted from the junction is amplified.

**envelope** – The glass housing of a lamp. (See also bulb.)

**filament** – The component of an incandescent lamp which generates light by thermal emission; the part that glows.

**flashlamp** – (See strobe lamp.)

**fluorescent lamp** – A lamp that produces light by exciting a phosphor with a plasma where the phosphor reemits the energy as light.

**flux** – The amount of energy per unit time (power) falling on a surface (incident flux) or emitted by a surface (radiant flux).

**getter** – The action of chemically removing contaminants during the normal operation of a device by causing them to be transported to some other location.

**halogen incandescent lamp** –

**HID** – Acronym for high intensity discharge.
**high-intensity discharge lamp** – A type of lamp that uses a gas plasma to generate light. Mercury vapor, metal halide, high-pressure sodium vapor, and low-pressure sodium vapor are the common high intensity discharge lamps.

**incandescent lamp** – An incandescent lamp filled with a halogen gas to getter the evaporated filament material from the bulb and redeposit it back onto the filament.

**lamp** – 1) A light source in which the light producing element is contained in a transparent or translucent housing (bulb) made from glass or plastic. 2) Any device with the purpose of producing light.

**laser** – Acronym for light amplification by stimulated emission of radiation. A device that produces a coherent, monochromatic, and usually somewhat collimated beam of light.

**LED** – Acronym for light-emitting diode.

**LIDAR** – Acronym for Light Detection And Ranging. A distance imaging technique, usually using a laser light source, for measuring the round-trip delay of a reflected light beam that is scanned in a raster pattern.

**light** – 1) Electromagnetic radiation detectable by the human eye, with wavelengths in the range of 380 to 780 nanometers. Also called visible light. 2) Less rigorously but more generally, it is electromagnetic radiation in the infrared, visible, and ultraviolet regions.

**light-emitting diode** – A semiconductor diode that converts a portion of the electrical energy in the junction to light that is nearly monochromatic. LED is a common acronym for light-emitting diode.

**lumen** – The unit of luminous flux. It is equal to the flux of one candela from a point source through a unit solid angle (steradian) or to the flux on a curved unit surface of which all points are at a unit distance from a point source of one candela. Abbreviated lm.

**luminous efficacy** – 1) The ratio for luminous power to radiant power at some specific wavelength. The ratio is one at 555 nm, and less than one for all other wavelengths. 2) For LEDs, the light flux output from an LED divided by the electrical power into the LED.

**monochromatic** – Light energy which is composed of only one wavelength.

**notching** – In an incandescent lamp, the effect of electrical current that causes localized thinning of the filament.
overdrive – In operating an LED in the pulsed mode, the ability to have the peak current exceed the steady-state current limit for the LED.

photometric response – Light measurements which are spectrally weighted to correspond to the photopic responsivity of a standard human observer.

quartz halogen – An incandescent halogen lamp with a quartz envelope. Quartz is preferred over glass because it can better withstand the higher bulb temperatures needed with the halogen cycle. Also, a quartz envelope transmits ultraviolet wavelengths blocked by a glass envelope.

radiometric – Light measurements in which all wavelengths of light are equally weighted; that is, the measurement is not weighted according the responsivity of the human eye.

speckle – A diffraction pattern having a granular appearance caused by coherent light, such as from a laser, reflecting off a rough surface or transmitting through a medium with some scattering (e.g. air).

strobe lamp – An arc discharge lamp that generates a very short burst of high intensity light. Used to obtain a sharp image of objects in motion.

wall plug efficiency – For LEDs, the luminous flux produced by the LED divided by the electrical power supplied to the LED (e.g., 80 lumens/watt). (See also, luminous efficacy.)
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