ELECTRONIC AUTOCOLLIMATOR FUNDAMENTALS

The electronic autocollimator is a high precision angle measurement instrument capable of measuring angular deviations with accuracy down to fractions of an arc-second.

It can be used in numerous applications in a variety of areas. Some examples include: perform a machine alignment, measurement of slide ways, precision machines, accurate optical assemblies, alignment of optical setups and more.

Measuring with an electronic autocollimator is fast, easy, accurate, and will frequently be the most cost effective procedure.

Used extensively in workshops, tool rooms, inspection departments and quality control laboratories worldwide, these highly sensitive instruments will measure extremely small angular displacements, squareness, twist and parallelism.

Duma Optronics offers a complete line of autocollimators designed to interface and display results digitally on a computer, the interface is easy via USB2 port. Our dual-axis, digital autocollimator incorporates the latest CCD technology and optical analysis software. Our newly introduced proprietary technology of laser analyzing autocollimator, which merges the autocollimation principles with beam analysis technology, offers the capability to simultaneously measure a laser beam direction and divergence in respect with the optical axis of the autocollimator.

Autocollimation Principle

An optical schematic illustrating the basics of autocollimation is shown in Figure 1. The system has a light source followed by a projection reticle. The light source is LED (usually 670 nm, IR versions were recently introduced). After passing through the beam splitter, the light enters the objective lens where it is collimated prior to exiting the instrument. Collimation means that the projected reticle is exactly one focal length away from the main surface of the objective lens. The projected collimated light is back reflected by a mirror, or other high-quality reflective surface, and is captured by the objective lens. The returned image appears in sharp focus on the high quality CCD detector. Due to the detector high sensitivity even very faint back reflection will be captured and displayed.

Deviation of the mirror by an amount A is causing deviation on the original line of sight by an amount of 2A. Assuming the amount of deviation of the reflective surface the focal length is denoted by FL, then mirrors' deviation is to be determined from the relationship: A=X/2FL

From the equation it is apparent that measuring mirror angular deviation is independent of the distance between the instrument and the reflecting surface.

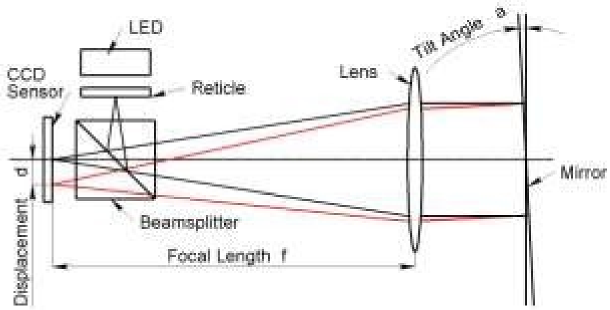


Figure 1

Deviations in azimuth and elevation can then be electronically determined and calculated by a computer. Furthermore the results are than clearly displayed on its screen. Resolution down to 0.01 arcsec is achievable. As a rule of thumb: the higher the FL - the higher the resolution. As a result, the field of view is smaller and thus it is more difficult to acquire the reflected signal acquisition.

The electronic method offers the advantage of complete objectivity in data recording, as well as a computer interface unlike optical autocollimators which are bulkier and less accurate.

In a telescopic application, where the telescope is calibrated to infinity, the angle of movement is A=X/FL.

In order to deliver accurately and produce intricate optical systems, a carefully designed method for interalignment is required, completing and updating the already existing methods. Thus, we designed and upgraded the performance of an electronic autocollimator and combined it with innovative mechanical manipulation of optical invariants such as a Lateral Transfer Hollow Periscope to greatly improve and expand inter-alignment procedures.

Inter-alignment of optical systems applications

Advances in sensor technology have opened the door to a new measuring instrument, based on autocollimation principles combining laser beam collimation and direction measurement, accurate telescopic measurement, focusing techniques with sophisticated software and computing techniques.

Laser analyzing autocollimator

Of special interest is the laser analyzing autocollimator since it combines laser-analyzing technology with angular reflection technology.

The technology presented allows combining data of the alignment autocollimator with incoming laser beam information to increase the overall performance and possible applications. Laser beam deviation is compared with autocollimator center and allows intricate alignment of lasers and optical elements to mechanical datum planes.

Due to the above features, the proposed device is potentially usable in aligning a laser beam to its mirrors as well as the alignment of a laser cavity and laser rods.

Moreover, the demand for greater precision in high-performance applications, especially in high power CO2 laser systems for automotive industries, has increased the use of these lasers. As higher accuracies for mechanical alignment combined with higher power levels can be achieved, optical alignment is a necessity.

The autocollimator device comprises of two instruments fused into a single unit; one being an electronic autocollimator and the second is a laser beam profiling system. This combination with some additional optics is very useful in the alignment and angular analysis of lasers and optical devices.

For increased capabilities, a new breed of autocollimators was designed with built-in laser beam profiling for analyzing incoming collimated beams for measuring divergence and incoming angle with respect to autocollimator's center. Moreover, by a built-in focusing knob, accurate center position of mechanical systems is possible.

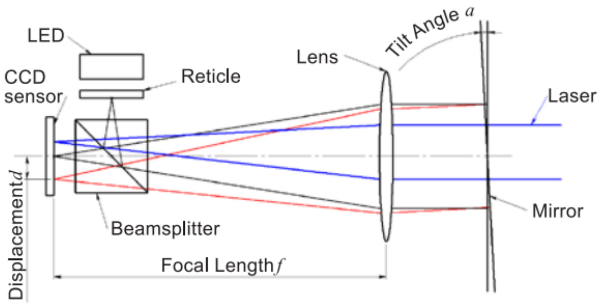


Figure 2

Figure 2 describes an autocollimator fused together with a CCD sensor capable for laser beam profiling, wherein its aperture accepts mirror reflections as well as an incoming laser beam. The software and a special filter slider allow simultaneous examination of relative angular deviation between the autocollimator and the incoming laser beam. This proprietary technology enables various alignments. For intricate alignment involving several optical line of sights, a proprietary device LOD was developed, in order to cancel the effect of parallax between lines of sights.

Lateral Offset Device (LOD)

The uniqueness of the Lateral Offset Device is that it can cancel the parallax between several lines of sights over an almost continuous distance. The LOD (Fig. 3) illustrates two Rotary Mounts orthogonally mounted with respect to each other and a Hollow Periscope fixed to the top Rotary Mount. The orthogonally mounted Rotary Mounts' purpose is to steer the periscope mounted on the top Rotary Mount. By doing so, the distance between an incoming light beam into the periscope and its outgoing direction is controlled.

Due to the above features, the proposed device is potentially usable for alignment or Boresighting between two parallel lines of sights or laser beams as well as the alignment of mechanical datum planes relative to other optical devices.

The Monolithic Hollow Periscope is based on two parallel mirrors with a given distance in between. The Rotary Mount is preferably mounted on a mechanical device serving as an optical bench.

For further understanding of the complexity of inter-alignment, the characteristics of several applications are to be described, namely: High power CO2 laser cavity alignment, testing accuracy of a beam delivery system and testing parallelism of rollers for mechanical processing.

Combining the laser analyzer autocollimator with an LOD opens the door to numerous intricate alignments that would otherwise be quite difficult and time consuming to produce.

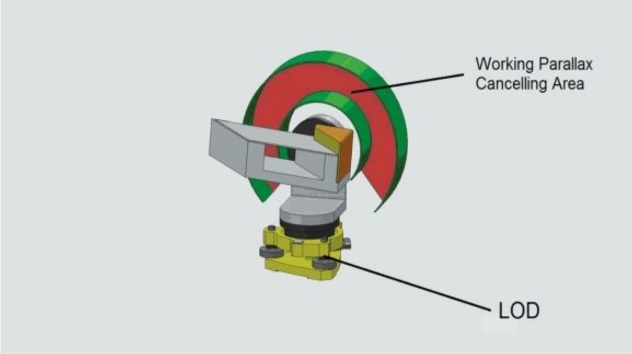


Figure 3: Lateral offset device

High Power CO2 Laser Cavity Alignment

There are many CO2 laser cavities configurations, however, we will concentrate our attention on high power applications where several tubes are working together with one resonator, and the laser beam is directed using folding mirrors.

Typical outputs are 600 W per meter of cavity length, with total laser beam outputs available up to 6 kW. Extending the length of the laser cavity is achieved by cascading several tubes along the laser cavity; folding the cavity using mirrors allows relatively compact CO2 laser to be built. Commercial CO2 lasers that use six tubes (and ten turning mirrors) are available and achieve high power output. The following image describes the working principle of CO2 lasers and typical folding configurations; 3D folding configurations can also be used.

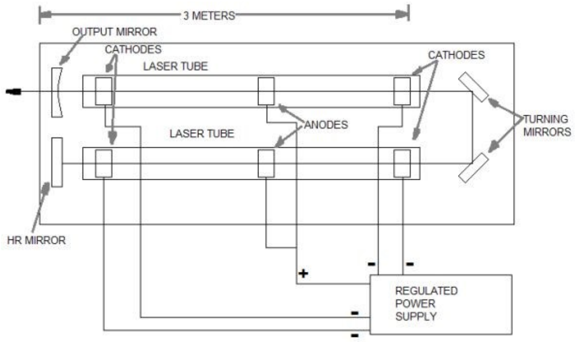


Figure 4: Axial Flow CO2 laser

Figure 4 above shows the preferred method of achieving an extended active length while minimizing overall dimensions and power supply cost. The optical cavity is folded once to utilize two plasma tubes positioned side by side. This is a relatively simple configuration, however, the same principles are applicable for more complicated cavities with stacked up tubes.

Proper alignment of an optical cavity is crucial, especially if stacked up. The laser beam and the optical cavity axis should completely coincide. It is critical that the laser beam couples completely to the fundamental (longitudinal) spatial mode of the cavity and not at all to the higher-order (off-axis) spatial modes. A transverse displacement or angular mismatch between the laser beam and the cavity can have an unwanted effect on the total beam power and its modes. By imposing strict alignment procedures, those effects can be minimized. Furthermore, alignment to mechanical datum improves production repeatability and downtime costs in case of laser replacement. The main alignment goals are as follows:

- Alignment of laser tubes to each other and mechanical datum

- Alignment of folding mirrors

- Alignment of pointing visible laser and cavity mirrors.

The following 3D solid drawing (Fig. 5) shows the necessary layout. We start by aligning the autocollimator to the mechanical datum by directing its line of sight to the reflective datum by using the pan and roll features of LOD. Next, by using the mounted V-blocks on the laser tubes, we align the tubes to be parallel to each other and mechanical datum. This is further achieved by the LOD device shifting the autocollimator's line of sight to the reflective elements mounted on top of the CO2 tubes and adjusting the tubes accordingly. An external laser can also be adjusted to the same line of sight and projected through the first tube towards the folding mirrors, enabling adjusting the folding mirrors until perfect parallelism between incoming and returned beam is achieved.

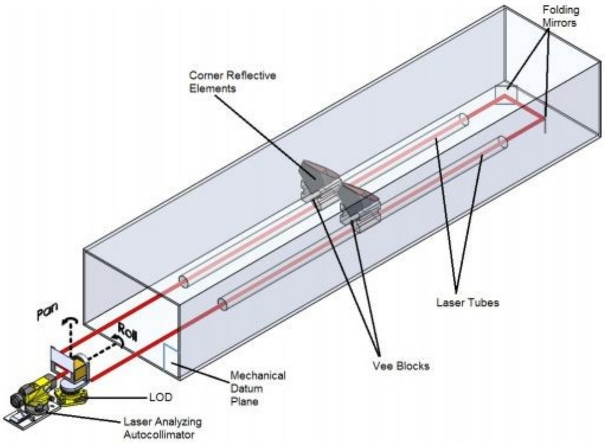


Figure 5: Alignment of laser cavity using laser-analyzing autocollimator

Laser Beam Delivery System

There are different configurations of industrial laser cutting machines: moving material, hybrid, and flying optics systems. These refer to the way that the laser beam is moved over the material to be cut or processed. For all of these, the axes of motion are typically designated as X and Y axis. If the cutting head may be controlled, it is designated as the Z-axis.

Flying optic machines must use some method to take into account the changing beam length from a near field cutting (close to resonator) to a far field cutting (far away from resonator). Common methods for controlling this include collimation, adaptive optics or the use of a constant beam length axis.

Characterizing factors for all flying optics systems is that the laser is stationary, and the beam is delivered by mirrors after a long path.

Five and six-axis machines also permit cutting formed workpieces. Also, there are various methods of orienting the laser beam to a shaped workpiece, maintaining a proper focus distance and nozzle standoff.

On flying optics machines, even minute changes in beam direction relative to the working table can cause large positional deviations due to the laser's long path. In other words, the deviation (D) is directly proportional to the angular deviation (A) multiplied by total path travel (T).

$D = (A) \times (T)$

-where D is the deviation,

-A is the angular deviation,

-T is the total path travel.

Thus, examining beam angle variations across the working table is a very important feature, and crucial for total accuracies in material processing by flying optics methods.

As shown in Figure 6, using the same basic instrumentation in a somewhat different configuration, we sample the beam direction as it hits the work area at several positions using the LOD and the laser analyzing feature of the autocollimator.

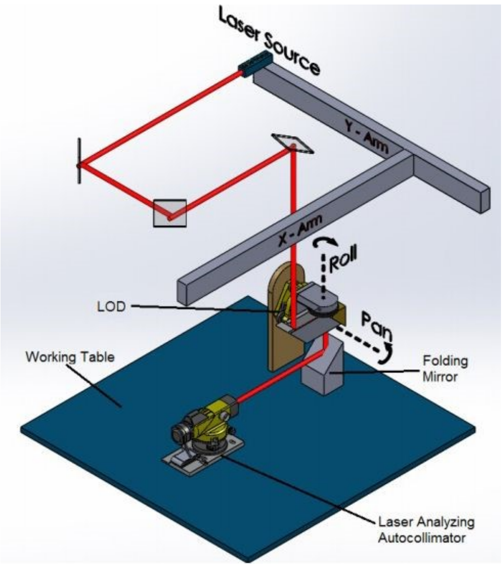


Figure 6: Examining beam angles on a working table

After examination, the focused laser beam will strike the material with perfect accuracy. The laser beam moves along the part contour, melting or welding as it goes.

Adjustment of Mechanical Parallel Rollers

Materials such as paper, plastic film, newspaper, wide bed printers, foil and metal sheets are often produced in long machines with multiple parallel rolls. These rolls are usually mounted on accurate bearings and are parallel to each other, having a significant alignment requirement regarding the parallelism between rollers. Parallel rollers prevent skewing of processed material as it passes through the processing path. Measurement of parallelism alignment of rolls is often impossible while the machine is processing the material.

Many companies need to check parallelism in-situ and as a preventive maintenance procedure. On completion of the measurement, a roller adjustment can be applied if required. Alternatively, the rolls may be replaced or overhauled depending on manufacturers specifications.

A new method of performing in-situ measurements is presented as follows (Fig. 7), where the measurement is performed by attaching a reference mirror to the end point of the rollers axis as shown in the schematic below. The mirror rotation is observed by the autocollimator through reflection; the reflected beam draws a perfect circle having a center coinciding with the axis direction of the rollers. By using the adjustable LOD the line of sight of the autocollimator can be moved from one roller to another. Perfect alignment is achieved when all circles generated by the rollers' end tip have the same center.

Furthermore, if the circle generated by the rollers is not perfect or wobbles, this can be easily spotted by the autocollimator and LOD. Rollers alignment is an important part of machine operation; a non-aligned device has a tendency to track off course and wander out of alignment during the processes. To avoid these problems, measurement and maintenance are crucial.

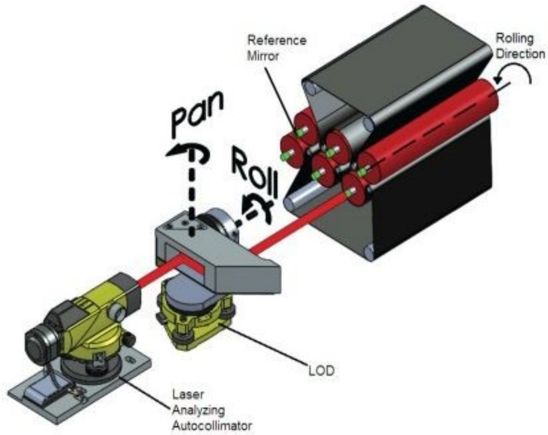
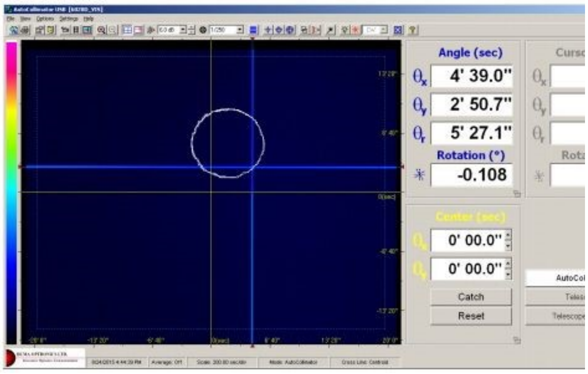


Figure 7: In-situ measurement of rollers misalignment

Automatic measurement based on these principles can yield web-guiding systems to be positioned just before a critical stage on a converting machine (for example, just before print station).



Angle (sec)
θ_x 4' 39.0"
θ_y 2' 50.7"
θ_r 5' 27.1"
Rotation (°)
-0.108
Center (sec)
θ_x 0' 00.0"
θ_y 0' 00.0"

Figure 8: Sample screen showing the rollers misalignment

Center of traced circle (Figure 8) is exactly at the center of rotation of one of the rollers. Perfect alignment of rollers' parallelism is when all reflected-traced centers have the same center.

OTHER APPLICATIONS

Measuring the straightness of machine components

The straightness of machine components, like guide ways, or the straightness of lines of motion of machine components, can be checked with the autocollimator and a base mirror. The base mirror is moved step by step along the guide way which is to be measured. When the mirror base is tilted, caused by lack of straightness of the slideway, the angle of tilt will be measured by the autocollimator. With this angle 'a' and the known base length b, the difference in height Delta, can be calculated:

$$\delta = b * \tan(a)$$

The slope of the line through the first and last point of the slideway depends on how the autocollimator has been set up. The measuring accuracy depends on the number of measuring points along the line.

The cross-axes of the autocollimator should be parallel to the horizontal and vertical directions of the plane where the measured line is in.

Measuring flatness

Measuring the flatness of large surfaces is usually done by measuring the straightness in the relevant direction of a series of lines in the surface plane in a certain pattern. The procedure for each line is the same as for single straightness measurements. By using an extra deflection mirror, all the lines of the pattern can be measured, while the autocollimator only needs to be placed in a few different positions. By correlating the straightness results, obtained along the lines, it is possible to determine the errors of flatness of the plane, related to a reference plane.

A short list of General various Applications

*Aircraft assembly jigs
*Satellite testing
*Steam and gas turbines
*Marine propulsion machinery
*Printing presses
*Air compressors
*Cranes
*Diesel engines
*Nuclear reactors
*Coal conveyors
*Shipbuilding and repair
(Civil and Military vessels)
*Rolling mills (steel, paper, sugar etc.)
*Rod and wire mills
*Extruder barrels

Optical measurement Applications

*Retro reflector Measurement
*Roof prism Measurement
*Optical assembly procedures
*Alignment of beam delivery systems
*Alignment of laser cavity
*Testing perpendicularity of laser rods in respect to its axis
*Real time measurement of angular stability of mirror elements.

ALIGNMENT BASED ON LASER BEAM TRAJECTORY

A Laser beam forms a straight reference line which enables accurate optical alignments for various purposes. Applying beams straightness to mechanical and optical application many measurements such as straightness, squareness and perpendicularity, parallelism measurements, run-out measurements, could be performed accurately over considerable distance with great accuracy. Very known applications are shaft alignment, optical cavities and rollers alignment.

Scientific and industrial applications seldom are characterized by systems which include multiple optical devices combined with accurate mechanics and lasers. To provide capabilities of alignment testing of intricate opto-mechanical systems carefully designed laser instrumentation will complete some already existing solutions.

Exploiting the laser beam's straightness characteristics, two basic technologies were developed- one is an AngleMeter, which accurately measures the deviation of the device in respect with the laser beam, and the second is the AlignMeter, which simultaneously measures the deviation in respect to the laser beam in four parameters: XY deviation in microns, and similar deviation in angular directions.

AngleMeter

The basic measurement principle for laser alignment is based on a simple fact that light propagates through space in perfect straight line from zero to infinity. However in our real world, there is some limitation to this statement since unlike space where light travels through vacuum, in a practical application the laser beam travels through air and it is influenced. This light characteristic forms the basic reference from which all laser alignment measurements and instruments are taken.

The Technology

The AngleMeter family uses an optical design similar to refractive telescopic sights and is classified in terms of objective lens F# and the its focal length. Drawing 1 describes a simplified representation of the AngleMeter optical design, which is based on an objective lens along with a detector placed exactly in its focal plane. A laser beam incident on the input aperture of the objective lens will be diffracted and focused at the detector surface. Its location on the detector surface is directly proportional to the angular deviation of the laser beam with respect to the AngleMeter optical axis. The angular deviation is calculated by AD=X/FL (focal length).

The objective lens diameter or input aperture is calculated by FL/F#. In general terms, larger objective lens diameters will allow larger laser beam angular deviations before laser incident point will be out of entrance aperture. Longer focal length will increase accuracy and resolution while decreasing the overall field of view. The appropriate combination of lens and field of view should be chosen on the basis of the required resolution and accuracy.

Optical parameters

AngleMeter instruments are usually designed for the specific application for which they are intended. Those different designs create certain optical parameters. Those parameters are:

Field of View — the ratio of detector active size to the focal length of objective lens yields the AngleMeter field of view. A field of view of 1/10 rad (5.7 degrees), for example, is produced by a 10 mm detector and a 100mm objective lens. The field of view depends on the application of the Angle Meter and the desired resolution.

Lower focal length leads to a higher field of view and easier initial alignment.

Objective lens diameter – The diameter of the objective lens determines the maximum laser beam size and its amount of movement on the entrance pupil. It is usually expressed in millimeters

Detection area- the incoming laser beam is focused on to the detector by objective lens. The detector converts the light position on its surface to an electronic signal; this signal is later processed by a computer to display accurate angular movement of incoming laser beam relative to the AngleMeter input aperture.

As shown in Figure 9, the detector could have two main types: CCD detectors and PSD detectors. For application of laser beams with short pulses a CCD detector is advantageous; however for high resolution alignment with CW lasers, position detectors are superior in performance.

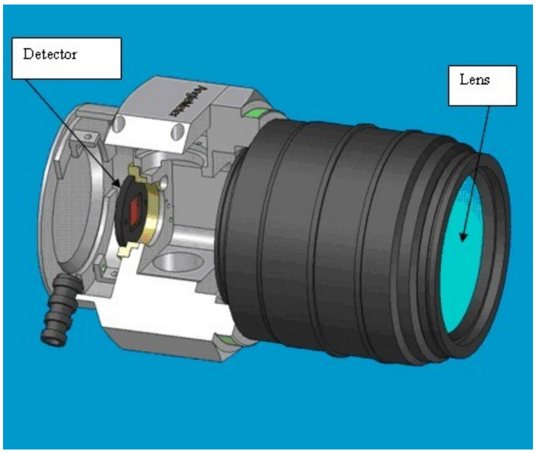


Figure 9 – AlignMeter Head

In today's modern technology, alignment accuracies are more and more demanding. Traditionally, alignment based on angular deviations was used, however, this measurement discards deviations in absolute position, usually measured in microns. A unique technology developed by Duma Optronics, will simultaneously measure the deviation of our device in respect to a laser beam in four parameters: XY deviation in microns, as well as $\theta x, \theta y$ in miliradian in respect to the laser propagation direction.

Using high resolution positioning technology, a device based on two detectors will automatically calculate the displacement of the laser beam across its surface as well as angular deviations to ensure that the measuring head deviations are recorded along the propagation of the laser beam.

The AlignMeter is offered in two basic configurations:

AlignMeter 50 mm, AlignMeter 100 mm. Typical resolutions for the 100 mm version are less than 1 micron for position and about 10 microradians for angular.

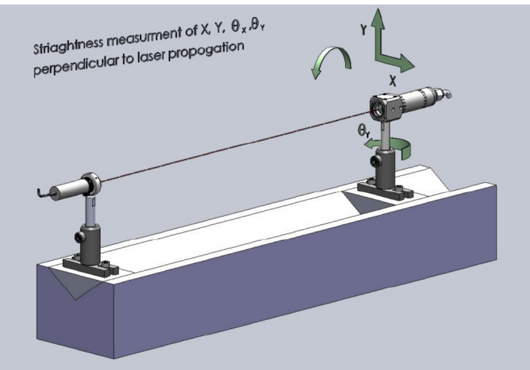


Figure 10

Figure 10 describes a typical application where a straightness of a beam should be measured. In one end of the beam an accurate and stable laser is stationary, and the AlignMeter system is moved along the beam, recording deviations in said 4-axis, thus characterizing beam performance as a function of distance between laser and AlignMeter head. In this specific application, the AlignMeter could be used for final inspection as well as a mean to correct beam deviations by mechanics. This system could also be implemented as a real-time measurement device to actively correct straightness in mechanical machines in applications related to the semiconductor industries and others.

Alignment of Hollow Articulated Arm

In this application, a schematic layout of a hollow articulated arm is displayed. An articulated arm is built as a multi-member device, wherein at each connecting knuckle, a mirror is used to reflect the incoming beam. If the mirrors are not perfectly aligned with the direction of rotation then the misalignment will cause the laser beam to deviate at the output end and thus render the arm to be inadequate for usage.

A typical articulated beam delivery arm comprises of a series of hollow tubes connected to rotational mirror knuckles. As shown in figure 11, a schematic representation of a hollow articulated arm, the beam travels through the tubes and is directed by the reflected mirrors along the tube axis. Connecting several knuckles and tubes allow multiple degrees of freedom, which is built by rotating each tube in respect to each other. This multiple degrees of freedom articulated arm can deliver the beam to a working volume by hand moving the end tip of the arm. Building a robotic beam delivery arm is a very challenging task due to the alignment problems of the rotating mirrors in the knuckles.

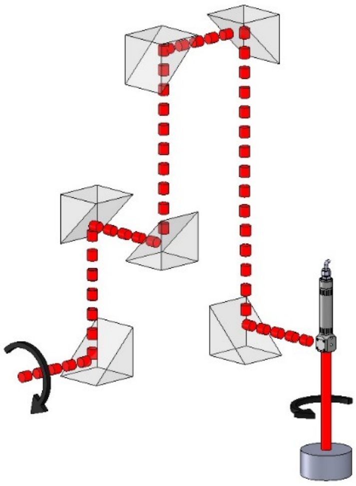


Figure 11 - Alignment of Hollow Articulated Arm

For initial alignment, one mirror should be replaced with our alignment sensor head, which will provide real time measurements of laser beam alignment as a function of arm rotation. Misalignment will be displayed as a circle directly representing the amount of misalignment of the mirror knuckle mounted before the sensor head. By aligning the mirror and repeating the rotation, the technician will bring the misalignment circle to a minimum, aiming for a zero circle radius. When done, the mirror will be re-installed and the next mirror will be removed and replaced by the Alignmeter. The process is repeated until all knuckle mirrors are adjusted- this will ensure that the output laser beam will travel perfectly at the center of the hollow robotic arm and its output will be located at the same point regardless of robotic arm articulation.