High Precision Refractive Scanner

By Michael Scaggs[1] & Gil Haas[2]

Introduction

Galvanometer scanners have been used for nearly three (3) decades for laser material processing. They are most commonly used for laser marking and have somewhat less utility in fine machining applications, in particular drilling precision holes and features below 250 microns. This limitation is due to their positional accuracy which is in the range of 2 to 10s of microns, depending upon the galvanometer and the F-theta lens used. Galvanometer-based systems are the simplest and least expensive way to direct a focused laser beam over a wide area. Nevertheless, they lack the "localized" precision for finite features over a large field.

A conventional multi-mirror galvometric system positions a focused laser beam by moving the beam in vectors. There are no "true arcs" generated for circular features. Instead, a circle is approximated by a series of short vectors. It is very difficult to form precision holes or any arc feature below 100 micron radius. Moreover, the angular resolution of the galvo motors is a further hindrance to the problem of small features and the attainment of high repeatability.

Galvo scanners are also subject to limited angular resolution and thermal drift which further restricts the ability of the device to machine precision features over a long period of time, e.g., a single production shift in manufacturing.

Non-galvo-based methods such as rotating, offset, wedge pairs (Risley Prisms) allow good precision below 250 microns, but only permit circular features and have a limited dynamic range and tend to be electro-mechanically complex.

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In the Risley prism design, the offset of the matched wedges causes an angular displacement of the laser beam from the optical axis. This angular deviation causes a lateral displacement of the focal spot when the angularly displaced beam is passed through a focus lens. The difficulty with this technique is that it is hard to coordinate the two wedges precisely at the high rotational speeds or to rapidly change the desired angle of deviation while the wedges are rotating. This approach usually requires a multitude of wedge pairs to cover a wide diameter range. The requirement to change wedge pairs adds significant time to replace and align; it is therefore unsatisfactory for most production processes.

Linear stages, in particular air bearing stages, offer a means of high precision. The linear or air bearing X-Y stage moves under a fixed focused laser beam, providing precision and accuracy. However, both air bearing and linear stages devices are expensive and have high inertia arising from moving such stages and the part supported by the stage so the speed of drilling precision features is limited.

Yet another approach used over the years is the focus lens itself can be placed offset from the optical axis and rotated or even placed in an open frame X-Y stage used to make all conceivable geometries. Mounting a lens in such a way is bulky and limited over the area that can be machined due to common lens aberrations.

Given the limitations of existing galvo scanners, the expense and inertia of linear stages, complexity and aberrations of other optical methods, there is clearly a need to have a device which offers the convenience and simplicity of a galvo scanner coupled with the precision of a linear stage.

New Method for Precision Scanning

A new, patent pending optical device (Neo*Scan*™ Scanner) offers a simple optical, electro-mechanical and software approach to directing a focused laser beam onto materials to machine simple and complex geometries. This novel structure provides the ease of use and simplicity of a galvo system but adds the “localized” precision lacking heretofore.

The innovative concept provides the precision and accuracy comparable to an air bearing X-Y stage that moves under a fixed focused laser beam but without the high cost and higher inertia of moving such a stage and the part. The device in its simplest description demagnifies the scan field by more than two (2) orders of magnitude and likewise the reputability and resolution.

A conventional scanner with fair resolution may have a scan field of 50 mm x 50 mm with an F-Theta lens having a focal length of 100 mm. This same scanner has great difficulty providing high accuracy of geometries below 250 micron, due to the angular resolution of the system and the fact that any curved features include a large number of short vectors.

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In a typical precision a laser galvo scanner that reflects a laser beam over an angular range of plus or minus (+/-) twelve to twenty degrees (12-20º) as the beam passes through a focusing lens, typically an F-theta lens. The angular repeatability of such a galvo is on the order of < +/- 22 μrad, which represents a resolution of ~ +/- 2.2 μm for a scan lens having a 100 mm focal length. The field of such a system will be f*(Tan Θ), where f is the focal length of the lens and theta is the angle the beam is reflected before the lens. A laser scanner operating then over a range of plus or minus twelve degree (+/- 12º) with a f=100 mm lens will therefore cover a distance of +/- 21.3 mm.

The optical deviation of a beam refracted through a thin optic is determined by the index of refraction of the material and the angle the optic is tilted. Tilting a two millimeter (2 mm) thick optical plate that has an index of refraction of 1.796 over a range of plus or minus twelve degrees (+/- 12º) degrees will cause a laser beam traveling on axis through said plate to deviate from the optical axis by plus or minus 0.188 mm. This increases the resolution of the same galvo by the ratio of 21.2mm/0.188 mm (113:1) which is better than two orders of magnitude.

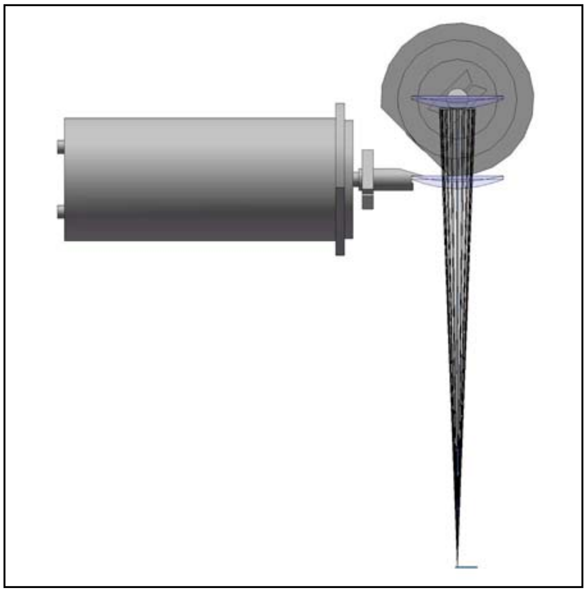

Figure 1: NeoScan refractive scanner with a pair of meniscus lenses mounted to galvos.

The NeoScan (a refractive scanner) uses the same control of the galvanometer but adds an optical demagnification that essentially maps, for example, a 50 mm x 50 mm field into a 0.2 mm x 0.2 mm field.

Figure 1 is the NeoScan in its simplest form and is comprised of a pair of inverted positive meniscus lenses. Each lens is mounted to a galvanometer to tilt each lens orthogonally to one another to displace the focus laser spot from the optical axis. The preferred optical material is the highest possible index material for the desired laser wavelength. Having a high index allows the thickness of the lenses to be as thin as possible to minimize optical aberrations and minimize the inertia of the galvo.

The focal length of the lens combination of the two lens system is defined by $1/f = 1/f_1 + 1/f_2 - t/f_1f_2$, where f_1 is the focal length of the first lens, f_2 is the focal length of the second lens and t is the separation between lens 1 and lens 2 where it is assumed for simplicity of description that the lenses are thin. The two lenses are tilted and naturally introduce coma, astigmatism and spherical aberration. Accordingly, the design of the lens curvatures, thickness and material are optimized to minimize the lens aberrations at the designed radial displacement from the optical axis.

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An inverted positive meniscus lens pair produces the fewest aberrations for the optical design as mentioned earlier. As well it is desired to have a high index optical material to facilitate longer radius of curvature surfaces and keep the optical elements as thin as possible to further minimize the aberrations and reduce inertia. Other lens curvatures can be used, e.g., a pair of plano-convex lenses; pair of double convex lenses, etc. Optical modeling has determined that the inverted, positive meniscus lens pair provides minimal aberrations and best optical performance.

The tilting of each of the two meniscus lenses causes the laser beam to be displaced in a controlled way from the optical axis. The amount of displacement is dependent upon the power of the designed lenses and the angle that the lenses are tilted about the optical axis and orthogonally to one another. In the system shown in figure 1 where the lens material is sapphire with an index of refraction of 1.796, a combined lens pair focal length of approximately 200 mm and a tilt angle of ten degrees (10º) of each lens, orthogonally, cause a radial shift of the focused spot by > 170 microns. Tilting the lenses beyond ten degrees causes the coma to become too great for usefulness

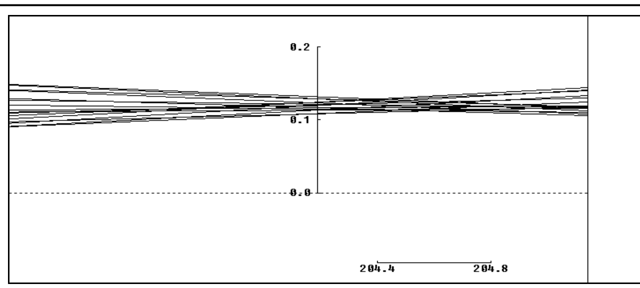

Figure 2: Enlarge view of ray trace of laser spot refracted away from the optical axis (dimensions in mm)

Fig. 2 depicts an enlarged ray trace at the focal point of the lens system on how the light is deviated from the optical axis from the corresponding tilt of first meniscus lens in the X plane in Fig. 1.

A second variation of the NeoScan refractive scanner (Figure 3) incorporates a conventional galvo. The beam exits the F-theta lens of a conventional galvo scanner and passes through a pair of parallel plates, each of which is mounted to a galvanometer. The parallel plate galvanometers are orientated orthogonally to one another so that the beam can be offset from the optical axis in a controlled way. The offset of the beam is determined by the angle of the plate, its thickness and the index of refraction of the plate.

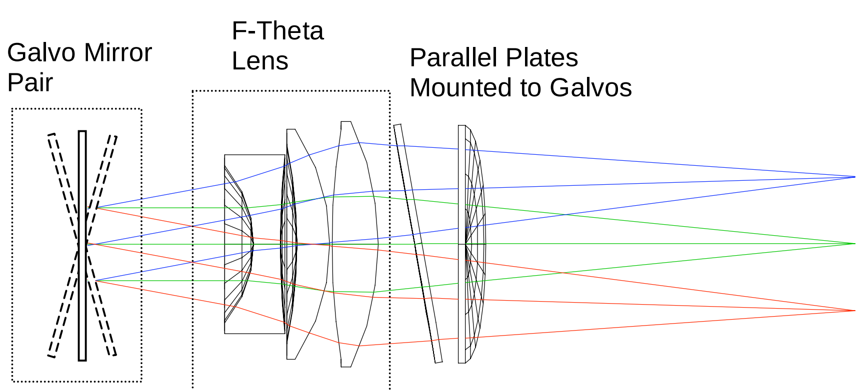

Figure 3: Large Field Refractive Scanner.

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The parallel plates permit the controlled shift of the laser beam passing through the scanner system and F-Theta lens. The plates are "thin" so the introduced aberration is minor spherical aberration and allows accurate machining of finite features over the large area of the scanner/F-Theta system which can range from a few millimeters to hundreds of millimeters, depending upon the rotation angle of the galvo scan mirror and the focal length of the F-theta lens. Through software control of the galvo pairs, features can be accurately machined over a field range limited only by the scanner/F-Theta system used.

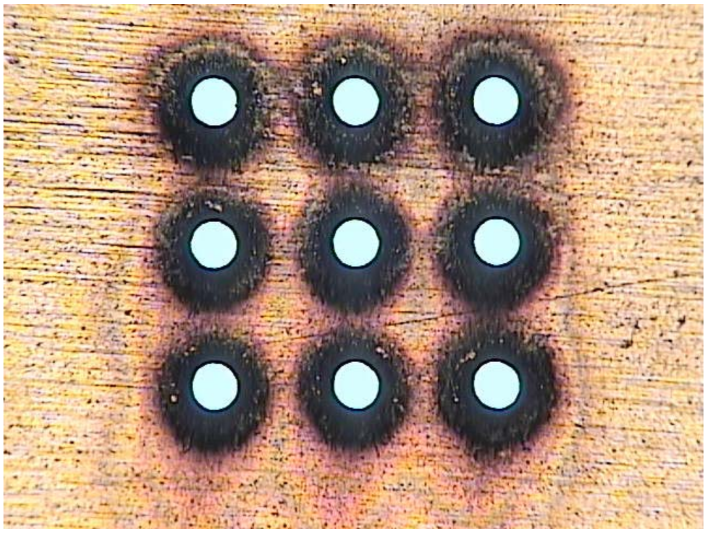

Figure 4: NeoScan Drilled Hole Array in Stainless Steel

The three ray traces (red, green & blue) in figure 3 represent the extremes of beam positioning by the "standard" galvo/F-Theta combination and at each extreme point the parallel plates mounted to galvos provides a higher degree of precision in the smaller field. Clearly a high degree of software synchronization between the mirror galvos and the refractive galvos is needed but would none the less provide a very versatile machining system.

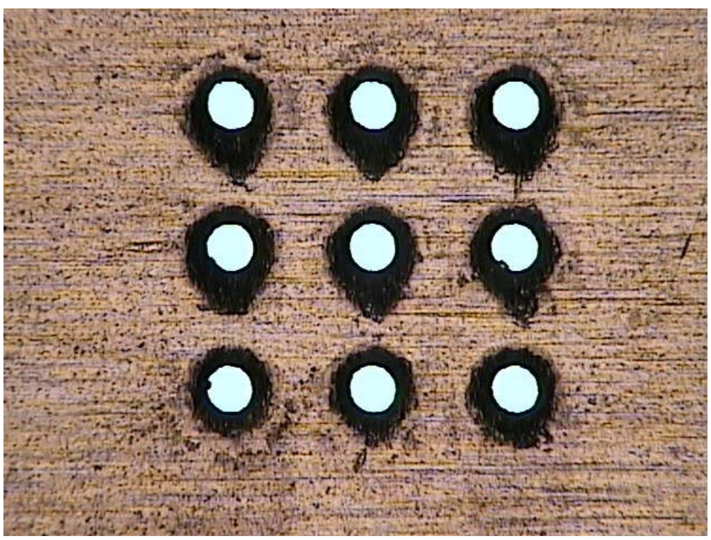

Figure 5: Conventional Scanner Drilled Hole Array in SS.

Another optical configuration of the NeoScan has a laser beam which pass through a simple, positive lens and then through a pair of plane, parallel windows. Each of the plane, parallel windows is mounted to a galvanometer motor and positioned orthogonally to one another. The only difference between this scenario and the previous one mentioned is that the second has a pair of galvanometer mirrors to deflect a laser beam through a scan lens (F-Theta type).

In all three scenarios of the NeoScan, the resulting focused light is directed onto a material such as a metal, plastic, glass or ceramic for machining; with the NeoScan refractive optical elements mounted to galvanometers and oriented orthogonally to one another.

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The NeoScan has a limited field, generally < 500 μm, that is determined by the index of refraction of the optical material and the angle of rotation, but nonetheless provides very high precision capability of features below 500 microns in size in a very simple opto-mechanical configuration.

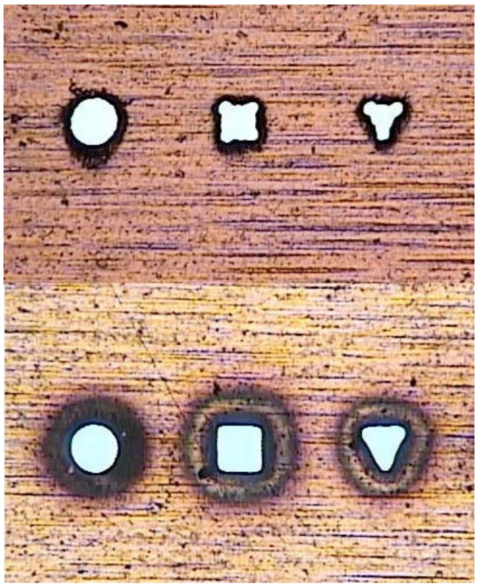

Figure 6: Conventional & NeoScan Scanner Machined Geometrical Shapes in SS

Figure 4 exhibits an array of nominally 155 μm diameter holes with a corresponding sigma of 0.049 machined with NeoScan refractive scanner in Stainless Steel using a 20 watt fiber laser.

In contrast figure 5 depicts nominally 155 μum diameter with a sigma 2.3 using a conventional galvo scanner (F-Theta Lens = 100 mm) drilled in stainless steel.

A comparison of Figs. 4 and 5 indicates that the refractive scanner consistently produces highly regular circular and repeatable holes over that of a conventional scanner.

Figure 6 shows a circle, square, and triangle machined in 80 um thick stainless steel by a conventional and the NeoScan refractive scanner; each having a nominal feature size of 150μm.

A comparison of the results in figure 6 indicates that the geometrical shapes formed in stainless steel by the refractive scanner are substantially true to idealized shapes and that the geometrical shapes formed by the conventional scanner are not. The reason for the variance between the scanners is the acceleration and deceleration time in relation to the time to form the feature. In the conventional scanner case the time to form the feature is too close to the acceleration/deceleration time where as in the refractive scanner it is considerably less and therefore not an overriding factor in the formation of the features.

Summary

The primary purpose of the refractive scanner is to create an optical system that precisely and repeatedly locates a concentrated laser beam and to manipulate the laser beam in such a way as to remove a wide variety of materials in a controlled way to generate complex geometries with excellent precision and repeatability. This is achieved through three different galvo-based refractive optical configurations. The best configuration is dependent upon they type of machining being done and how large a field is required.

It is important to note as well that the refractive scanner can compensate for irregularities in the focused laser beam. If a focal spot of the focused laser beam is elliptical, for example, the scanner can be programmed to move in an opposing elliptical manner to compensate and achieve a perfectly round hole despite imperfections in the laser beam.

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