A Proposal for the design of a 1m^3 volume three-dimensional scanner

Summary

The three-dimensional digitisation of a part must be done following the specifications of accuracy, resolution, repeatability and speed.
Usually, accuracy is desired to be as high as possible, since it gives a measure of how similar is the digitised object to the real one. The more accurate is the digitisation, the more accurate will be the measurements. Resolution tells about the point density, i.e. how

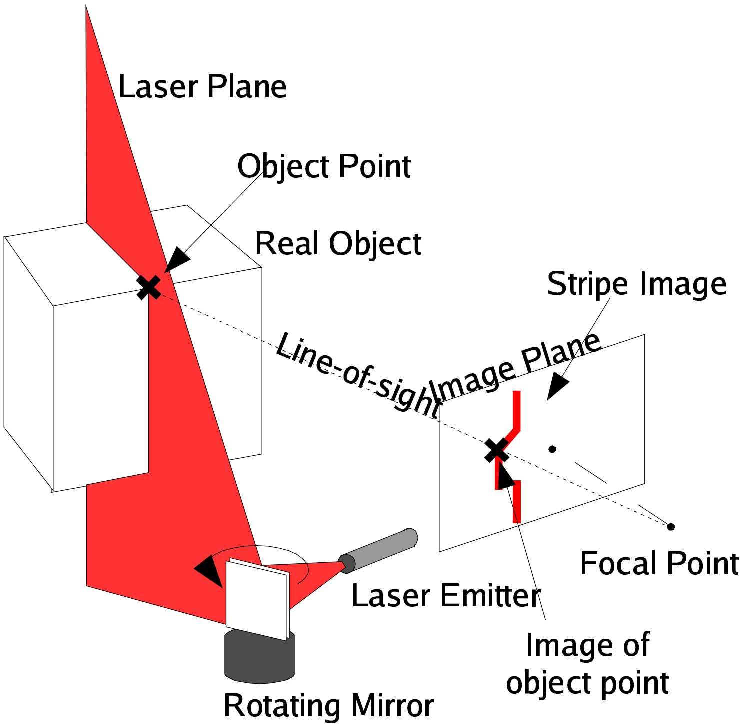

Figure 1: The principle of triangulation

close to each other are two consecutive points of the digitised part. Finally, repeatability shows how *spread* are different measurements of the same point.
Different aspects influence on the features summarised above, so in order to maximise accuracy, a high resolution image sensor sould be used, a tradeoff between compactness and baseline (separation between camera and light emitter) must be identified, and subpixel accuracy peak detection should be employed in order to get the horizontal position of the light stripe as accurately as possible. In the following sections all these aspects are discussed and the influence of noise in the 3D reconstruction is reported.

The principle of triangulation

Triangulation-based scanners rely on the geometrical relation between the image plane and the light emitter. Figure 1 shows this principle graphically. The image of a point on the object together with the focal point of the camera define a line-of-sight. Computing the intersection between this line-of-sight and the light stripe, the three-dimensional coordinates of the object point are obtained.
However, in order to be able to perform the intersection calculation, a previous step where the different geometric parameters of the system (i.e. The camera pose, the light source pose, the camera intrinsic parameters, etc...) are computed is required. This step is known

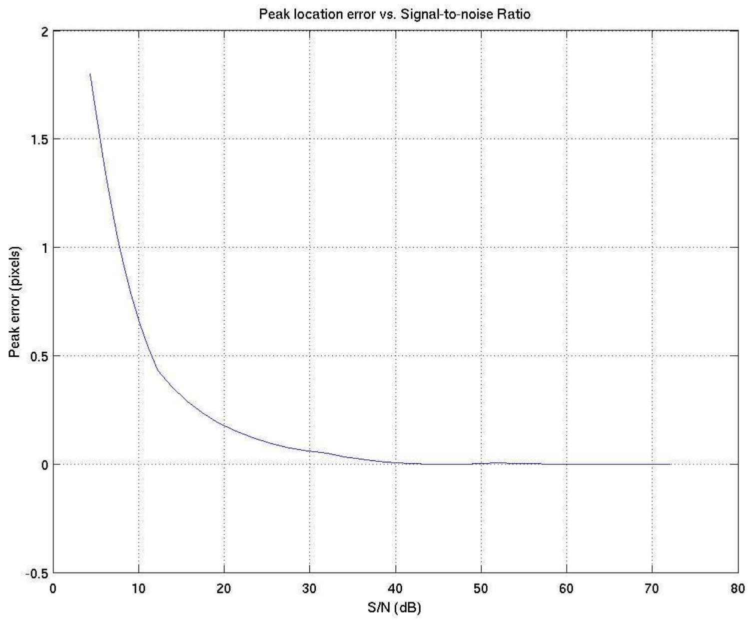

Figure 2: Influence of electric noise in the peak location

as calibration process and it is critical if maximised performance is required.
In order to avoid the accurate measurement of camera and light source respective poses, projective calibration will be used. Using projective calibration, it is assumed a simple linear pinhole model for the camera, where no distortion is present. This assumption is feasible if the proper lenses are used, given a determined image sensor size.
Even if distortion is present, projective geometry techniques can be adopted in order to remove it, although accuracy may be seriously affected.

The influence of electrical noise on the sensor

Electric noise has a significant influence on the image *"quality"* of any image sensor. Hence, since image sensors are used in triangulation scanners, the influence of such noise source must be identified and quantified.
Multiple electric noise sources arise according to their respective nature i.e. *dark current noise*, *photon shot noise*, *fixed pattern noise*, etc. All these noise sources have a global effect, which can be quantified in terms of Signal-to-Noise-Ratio. Figure 2 shows how the cummulative effect of noise influences in the determination of the laser peak location. The measurements shown in figure 2 where obtained by simulation, assuming a statistic gaussian distribution of noise, evaluated with different values of σ, which is in fact the amplitude of the noise *"signal"*. As it can be expected, the higher is the SNR, the smaller is the peak location error, and hence, the three-dimensional reconstruction.

Fundamental limits to accuracy

Fundamental limits are the physical limits which can not be *passed*. That is, the upper limits to the system performance, or, to put it more clear, *something we MUST live with*. Two main such limits appear; the former is related to the image sensor, and the latter comes from the light source.
The image sensor's fundamental limits come from both technology and physics. When using CMOS image sensors, dark current is a technology issue, and it is a function of temperature, hence a low dark current sensor should be selected in order to minimise the effect on accuracy. In addition, optical photon shot noise and reset noise (or kTC) are the

most influent fundamental limits.
The critical point is that the more significant are the sensor's fundamental limits, the lower is the maximum frame-rate. Hence, fundamental limits of the sensor have significant influence on the performance when very short light exposures are required.
The light source fundamental limits are very significant when coherent light sources are used (as when laser light is used, which is the most typical case). Laser light fundamental limit is called *Speckle*. Speckle arises in an image when the surface is rough compared to the optical wavelength. The result is random variations in the relative phases of the imaged points. That is, brighter and darker points within the stripe width (see figure 3).
Usually a gaussian distribution of light energy is assumed (because it is physically true) in a laser spot (see figure 4), although it is not exactly *seen* this way by the image sensor, due to speckle.

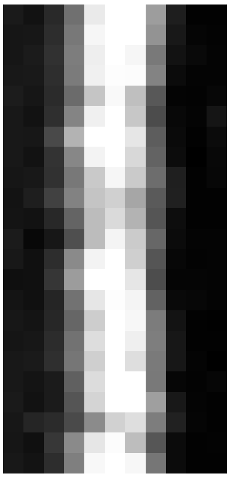

Figure 3: The effect of Speckle

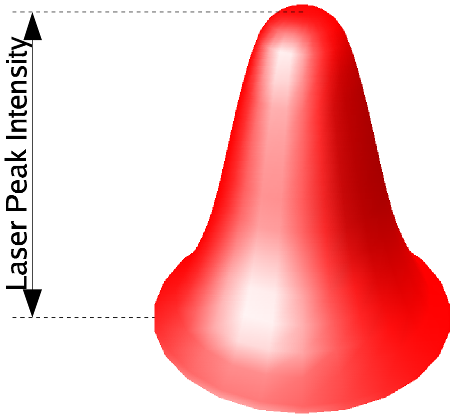

Figure 4: Laser optical energy distribution

Maximisation of performance

In order to maximise the three-dimensional reconstruction features, the image sensor must be selected so it exhibits an optical photon shot noise as low as possible, together with low FPN (Fixed Pattern Noise) and dark current.
In addition, if acquisition speed is to be maximised, a fast image sensor should be used. Furthermore, CMOS image sensors are required due to their windowing capabilities, since windowing allows an even higher image transfer rate, not paralleled by CCDs (the transfer rate is directly proportional to the amount of pixels to be transferred to the processing stage), because it actually crops the image that *sees* the imaging system.
Finally, laser technology should be able to provide *speckle-free* coherent light, which can be achieved by using a standard optical frequency shifter. In addition to the removal of speckle, the laser light source should be power tunable. That is, the output power should be *modulable* in order to be able to select the right performance given a particular object reflectance.
In order to keep accuracy at the desired levels, provided that a big volume (typically $1m^3$) must be digitised, the image sensor resolution is a critical issue. As an example, consider an object size of 500 x 500 mm digitised from 1m distance with a 2/3" sensor, with a pixel size of 6.45 x 6.45 um and a resolution of 1360 x 1036 pixels. The light source is a speckle-free 650nm wavelength laser. The SNR has been taken to be 32dB (medium). Under these circumstances, the range accuracy is estimated to be 10um.