Laser micromachining by ablation has proved to be a useful technique in many fields of advanced manufacturing. In addition to established industrial applications, such as the drilling of ink-jet nozzles and printed circuit board via holes, new applications are emerging, particularly in the areas of optics and microelectromechanical systems (MEMS), that are ever more challenging in terms of geometry, machining accuracy, surface finish and/or processing speed. In the MEMS domain, these new applications are mainly in areas where 3D processing of polymers and/or glasses is required, such as micro-fluidics [1] and RF MEMS [2]. The most important emerging optical application is the production of plastic micro-lens arrays for large area displays [3]. This is particularly challenging because it requires rapid processing of highly uniform, optical quality components over extremely large areas (up to 1.5 x 2 m²).

Laser machining of complex surfaces may be carried out either in direct-write mode, where a focused laser spot is scanned over the workpiece, or in mask projection mode, where an imaging lens is used to project a mask pattern. Lasers with high repetition rate but relatively low pulse energy, such as bench-top DPSSL (diode-pumped solid state) lasers, are normally used in direct-write mode. Mask projection tends to be reserved for excimer lasers, where the higher peak power allows parallel processing over large areas.

Here we discuss two excimer laser micromachining techniques that allow both 3D structuring and large area processing: synchronized image scanning (SIS) and half-tone mask projection. Experimental results are presented for polycarbonate cylindrical micro lens arrays produced by both techniques.

**Large area and 3D excimer laser micromachining processes**

Projection ablation systems typically include beam forming optics designed to produce uniform illumination at the mask. With a standard binary mask (zero or 100% transmission), each laser pulse removes material to the same depth in all exposed regions of the workpiece. Several methods can be used to produce features with variable surface height in such systems. One approach is to vary the shape and size of the mask aperture during machining, either by using a motorized aperture [4] or by indexed mask projection (IMP) which uses a sequence of different static mask apertures [5]. An alternative approach is to move or ‘drag’ the workpiece under a static mask while firing the laser.

With the laser fluence and firing pitch (the distance travelled between laser pulses) held constant, workpiece dragging produces a uniform channel with a cross-sectional profile defined by the mask aperture shape. The technique is well suited to producing periodic structures over large areas, and has been widely used in the fabrication of structures such as gratings, microchannel arrays and anti-reflection surfaces [6].

Synchronised image scanning [3] is a variant of the above techniques in which the workpiece is dragged beneath a linear array of IMP mask apertures, all of which are illuminated by the laser beam. The laser firing pitch is set equal to the spacing between mask apertures so that each site on the workpiece is exposed to a single pulse with each of the apertures in turn. This concept is illustrated in figure 1. SIS offers higher throughput than indexed mask projection by virtue of parallel processing. Also, because each site receives only one pulse with each SIS aperture, the stepping in the surface that arises from using a discrete set of masks can be minimized.

The above techniques achieve variable depth by exposing different parts of the workpiece to different numbers of laser pulses, with the fluence in the exposed regions being independent of position. An alternative option, also illustrated in Figure 1, is to have the same number of pulses everywhere, but vary the local fluence using a half-tone mask. A half-tone mask comprises an array of pixels, each with an opaque region of well-defined area on a transparent background. Provided the pixel structure is not resolved by the projection optics, such as mask will behave simply as an attenuator, with the local transmission being proportional to the square of the transmissive area in each pixel. In this way a conventional binary mask can be made to behave like a continuously variable or grayscale mask. Figure 2 shows some examples of optical components fabricated by ablation using static half-tone masks.

Half-tone masking has been used previously with projection ablation to produce diffractive optical elements [7], microfluidic channels [8] and other microstructures [9,10]. It is an attractive option when producing isolated 3D structures because it is less costly in terms of mask real estate than SIS. However this advantage is lost in large-area applications where parallel processing becomes imperative, requiring an array of half-tone apertures.
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Other factors also need to be taken into account when choosing between the different approaches, such as process efficiency and surface finish. These aspects are discussed below.

Process and mask design
For any given combination of laser source and material, the first step in designing a laser micromachining process is to decide on the operating fluence (the maximum pulse energy per unit area incident on the workpiece). In general the material removal rate, the morphology of the machined surface, and the nature and amount of ablation debris will all depend on the fluence, and these aspects can only be explored by experiment. For large area applications, the process efficiency in terms of volume of material removed per joule of incident laser energy is also an important consideration as this sets an upper limit on the throughput for a given laser source.

SIS mask design
When designing an SIS mask, a CAD drawing of the target structure is divided into a number of horizontal slices, as shown in Figure 1, with the outline of each slice being used to define an SIS mask aperture. This process is similar to that used in rapid prototyping, and CAD tools have been developed to automate the process [3]. Secondary effects that can lead to non-uniformity in the ablation rate across the workpiece, such as the reduction of ablation rate on inclined surfaces, are usually ignored for simplicity. Ideally, the thickness of each slice is chosen to match the ablation depth per pulse at the chosen operating fluence so that the machining process can be completed in a single pass.

Half-tone mask design
Mask design for half-tone ablation involves deriving a mask transmission function \( T(x,y) \) from a height map \( h(x,y) \) of the desired structure. These two functions are related through the material ablation curve (material removal rate versus laser fluence). An important feature of half-tone ablation, which sets it apart from the other techniques described above, is that detailed knowledge of the ablation curve is required over a range of fluences; it is not sufficient just to know the ablation depth per pulse at the operating fluence.

The operating fluence and number of pulses must be chosen so that \( T(x,y) \) lies within the achievable range of transmission levels at all points. This range is set by the resolution of the projection lens (which determines the maximum size for each half-tone pixel), and the mask-masking technology (which limits the minimum feature size within each pixel).

In practice the minimum allowable transmission is often determined by the material ablation characteristics rather than by the half-tone mask technology. For most materials there is a minimum useable fluence below which ablation debris is not ejected effectively and hence accumulates on the machined surface. For polycarbonate machined at 248 nm wavelength this occurs at around 100 mJ/cm². This minimum fluence requirement translates to a minimum machined depth in the final structure, so that in general it is not possible to produce structures where the depth varies continuously down to zero.

The minimum fluence requirement generally implies removal of material that does not form part of the final structure, and consequently the process efficiency of half-tone machining tends to be lower than that of the other mask projection techniques. This is not a major issue for R&D or prototyping, but is an important consideration when it comes to large scale production [11].

Additional considerations
The mask design methods outlined above tend to become less accurate in deeper structures as a result of diffraction, illumination-related effects, and the reduction of the ablation rate on inclined surfaces. For structures such as microlenses where the surface height is relatively slowly varying, the latter effect appears to be most important. If neglected during the mask design stage, the angular variation of the ablation rate can lead to significant errors in the depth profiles of deeper structures. Furthermore, for any given operating fluence there will be a limiting surface gradient that cannot be exceeded, and this can lead to unwanted artifacts such as seams of material at the interfaces between adjacent regions that have been machined at different times. Such effects can only be eliminated reliably by taking account of angular dependence of the ablation rate during mask design, which in general requires the use of numerical modeling. We have been developing simulation tools that can address this problem [12], and have demonstrated a significant improvement in profile control for structures with depths of up to several hundred microns [13].

In addition to the above issues which relate to the overall profile accuracy, there are other features of the SIS and half-tone processes relating to surface morphology that cannot currently be modeled. For example, the running order of the SIS apertures can have a marked effect on the roughness of the final surface. In particular, the stepping is reduced if the boundary of each aperture lies inside the one that follows it. In qualitative terms this is because the steps caused by the hard edges on each aperture become rounded by subsequent exposures. The net effect is that the surface steps in the final structure can be significantly smaller than might be expected based on the ablation depth per pulse.

Application example – microlens arrays for 3D displays
To explore the capabilities of half-tone ablation and SIS in terms of profile accuracy and surface finish, we have fabricated polycarbonate microlens arrays typical of those in 3D display applications. Convex cylindrical lenses were machined with a width of 650 μm and a radius of curvature of 1 mm, corresponding to a maximum machined depth of around 50 μm and a maximum surface slope of 18°. Experiments were carried out with an Exitech M6000 laser micromachining workstation designed specifically for SIS. The workstation was equipped with a KrF excimer laser, a 5X 0.15NA projection lens, and beam-forming optics configured to produce a 70 x 6 mm² rectangular illuminated region at the mask plane.

An operating fluence of 250 mJ/cm² was used for the SIS process, corresponding to the peak of the process efficiency curve. At this fluence a total of 544 pulses was required to achieve the required maximum depth. These were delivered in two passes, using an SIS mask with 272 apertures on a pitch of 250 μm (corresponding to a laser firing pitch of 50 μm). A higher fluence of 890 mJ/cm² was used for the half-tone process to minimize the effects of the minimum fluence requirement. In this case the desired cylindrical lens structure was produced by dragging a 4.75 mm-long rectangular half-tone mask aperture with the required transverse transmission profile. A total of 288 pulses was delivered in a single pass, requiring a laser firing pitch of 3.3 μm. Figure 3 shows an SEM image of the structure produced by the half-tone process.

Figures 4a and 4b compare stylus profilometer measurements made on individual half-tone and SIS lenses (solid lines in figure 4a and 4b respectively) with the expected
It was found that the periodic component could be eliminated by flood exposing the surface with a small number of laser pulses at a much lower fluence. This 'polishing' process was carried out by workpiece dragging using a simple rectangular aperture with a single half-tone transmission profile on its leading and trailing edges. Figure 5 (middle) shows the surface profile after polishing, which has an Ra of only 8.4 nm. The improvement in surface finish achieved by polishing is also evident in the phase plot on the right of Figure 5, which shows a significant reduction in the noise on the fringes after polishing.

DHM measurements at the equivalent position on a lens machined by SIS (Figure 5 [lower]) also show a periodic component in the linescan which corresponds to the laser firing pitch, but even without polishing the Ra was found to be comparable to that of the polished half-tone lens. However, this comparison is somewhat unfair to the half-tone process because the crown of the SIS lens receives only a very small number of laser pulses, and indeed Ra values as high as 30 nm were measured elsewhere on the surface, compared to a maximum Ra of around 20 nm on the as-machined half-tone lens. The overall performance of both processes in terms of surface finish was found to be appropriate for the intended large area display applications.

Conclusions
Several processes are available for large-area excimer laser micromachining of complex surfaces by projection ablation. We have focused on two techniques: SIS and workpiece dragging with half-tone masks. Based on results to date it would appear that SIS is the most appropriate technique for large area machining because of its higher process efficiency. Excellent surface finish has been achieved in polycarbonate, and it is expected that further improvements will be made by implementing SIS masks with graded transmission profiles at the edges. Half-tone masking remains an attractive option for small area applications because of its more efficient use of real estate on the mask.

Acknowledgements
This work was funded by the UK Engineering and Physical Sciences Research Council (EPSRC). Experiments were carried out using laser facilities kindly provided by Eutech Ltd. J.E.A. Pedder was supported jointly by the EPSRC and Eutech Ltd. The authors are grateful to Karl Boehlen for his help and advice with the SIS work. The DHM measurements were carried out at favourable rates by Lyncée Tec SA, Lausanne, Switzerland.

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See Observations p37