INTRODUCTION
The optical components with micro structure have been extremely developing and applied to optoelectronic devices for the past decade [1-3], such as light uniform for micro projectors and the light guide plate for liquid crystal display (LCD). The most used structures are one or multi-direction V-groove and micro lens array. The processes for manufacturing of such micro structures could be categorized into micro-system technologies and micro-engineering technologies [2]. To get high three-dimensional form accuracy, micro-engineering technologies such as fly-cutting, micro milling, grooving, and fast tool servo (FTS) are more suitable for micro optical structure fabrication. In this study we focus on the micro lens array fabrication using FTS. In general, the micro lens array consists of spherical lenses and could be fabricated by diamond turning with FTS. It performs high efficiency and high surface quality. With FTS, diamond tool could have a small and fast motion during the turning processes. Since the diamond tool radius needs to be taken into account for the diamond tool path generation, it is very difficult to get an analytic solution for micro aspherical lens array machining. In this study we use the over cutting depth compensation to approach the diamond tool path of FTS machining for micro aspherical lens array. In following sections we introduce the tool path generation of FTS for micro aspherical lens array fabrication in detail; for verification, a micro lens array with parabolic surface was cut and measured by the ultra precision machining machine (FF705XG, from Precitech) and ultrahigh accurate 3-D profilometer (UA3P-4, from Panasonic) respectively.

FTS AND ITS TOOL PATH GENERATION
FTS machining configuration is shown in FIGURE 1: the FTS controller receives the X-position and working spindle angle from the diamond turning machine, and calculates the FTS actuator stroke. The algorithm of FTS stroke is defined by the micro lens array specifications and diamond tool radius, and then written in C-language and complied in the SOP interface software. SOP is the software name abbreviated in German and means the controlling system for high precision manufacturing of surfaces [5].
Then the lens center position could be found as:

\[ Y_{cen} = Y_{row} \cdot Y_{p} \]

(3).

As shown in FIGURE 2, \( e \) and \( f \) are the distance between the cutting point and lens center along the cutting concentric direction and radial direction respectively, and \( r_s \) is the distance between the lens center and working spindle center along the cutting radial direction. These geometric parameters could be calculated as follow:

\[ e = \left[ \cos(\theta + \pi/2) \sin(\theta + \pi/2) \right] \left[ \frac{X_{cen}}{Y_{cen}} \right] \]  

(4),

\[ r_s = \left[ \cos \theta \sin \theta \right] \left[ \frac{X_{cen}}{Y_{cen}} \right] \]  

(5),

\[ f = r_s - r \]  

(6).

To get the correct lens surface profile, the diamond tool radius needs to be taken into account. For spherical lens surface, the diamond tool path with tool radius compensation is always circular path with radius as \( R_{ls} + r_s \) and \( R_{ls} - r_s \) for convex and concave spherical lens respectively. \( R_{ls} \) is the radius of the cross section of the lens surface of cutting radial direction and \( r_s \) is the diamond tool radius. Since cross sections without lens center have different aspherical surface profile, micro lens array with aspherical lens surface profile is very difficult to generate diamond tool path with tool radius compensation. If the diamond tool path follows the aspherical surface profile without tool radius consideration, the surface would have over cutting problem. As shown in FIGURE 3, the over cutting depth \( E_z \) approximates to \((1/\cos \alpha - 1)r_t\), where \( \alpha \) is the tangential slope of the aspherical profile at the cutting point. In this study we develop the diamond tool path of FTS for micro aspherical lens array, and the diamond tool radius compensation is set as \((1/\cos \alpha - 1)r_t\). The tangential slope of the aspherical profile at the cutting point could be gotten by partial differential to the standard aspherical surface equation with respect to the offset along the cutting radial direction.

In general, an aspherical lens surface profile has a standard formulation as:

\[ Z = Z(h) = \frac{c h^2}{1 + \sqrt{1 - (1 + k) c^2 h^2}} + \sum_{i=2}^{n} A_i h^{2i} \]  

(8),

where \( h \) is the lateral distance from the lens center and has relationship with \( e \) and \( f \) as:

\[ h^2 = e^2 + f^2 \]  

(9).

Substituting equation (9) to equation (8), we can...
get:
\[ Z(e, f) = \frac{c \cdot (e^2 + f^2)}{1 + \left[ 1 - (1 + k) \cdot c^2 \cdot (e^2 + f^2) \right]^{1/2}} + \sum_{i=2}^{n} A_{2i} \cdot (e^2 + f^2) \]  
(10).

It is the function of \( e \) and \( f \) to describe the surface profile. If the diamond tool path follows the lens surface profile without diamond tool radius compensation, there would be surface height error in cutting radial section as:
\[ E_i = \left( \frac{1}{\cos \alpha} - 1 \right) r_i = \left[ 1 + \tan^2 \alpha \right]^{1/2} - 1 \]  
(11).

Eq. (11) shows that the surface height error depending on cutting radial slope and diamond tool radius. Cutting radial slope could be found by partial differential with respect to \( f \), as shown in following,
\[ \tan \alpha = \frac{\partial E}{\partial f} = 2 \cdot c \cdot f \left[ 1 + \left[ 1 - (1 + k) \cdot c^2 \cdot (e^2 + f^2) \right]^{1/2} \right]^{1/2} \]  
\[ + (1 + k) \cdot c^2 \cdot f \cdot (e^2 + f^2) \left[ 1 - (1 + k) \cdot c^2 \cdot (e^2 + f^2) \right]^{3/2} \]  
\[ + \sum_{i=2}^{n} 2 \cdot i \cdot A_{2i} \cdot f \cdot (e^2 + f^2)^{i-1} \]  
(12).

Finally, the fast tool servo stroke with tool radius compensation can be represented as:
\[ Z_{str} = S - Z(e, f) - E_z \]  
(13),

if \( S - Z(e, f) - E_z \leq 0 \), \( Z_{str} = 0 \)

where \( S \) is the sag of lens center relative to the lens edge.

Theoretically, one should use a small radius diamond tool to reduce the form error due to the tool over cutting as shown in Eq. (11). But the disadvantages are the worse surface roughness and poor cutting efficiency. To reduce cutting remained concentric groove, it is better to use a bigger radius diamond tool. For this reason we develop the diamond tool path with over cutting depth compensation.

**Cutting and measurement of micro parabolic lens array**

To verify the above method of tool path planning, a rectangular micro parabolic lens array was cut and measured. The optical parameters of the micro parabolic lens array are: vertex curvature \( c = 1/30\text{mm}^{-1} \) (concave), conic coefficient \( k = -1 \), center sag \( S = 60\mu\text{m} \) lens pitch \( X_p = Y_p = 4.5\text{mm} \), and the diamond tool radius is 0.5mm. We wrote a C-language program based on given parameters and above equations, then compiled it using SOP software. Figure 4 shows the compiled and simulated result.

After all the preparation process, we used the ultra-precision machining machine FF705XG equipped with fast tool servo FTS 70 to cut the micro parabolic lens array and the ultrahigh accuracy 3-D profilometer UA3P-4 to measure its form accuracy. Figure 5 shows the form accuracy of the center lens, and it is 0.3055\(\mu\text{m}\). Figure 6 and 7 show the form accuracy of upper and right lens, and they are 0.2998\(\mu\text{m}\) and 0.2880\(\mu\text{m}\) respectively. As shown in Figure 5, there exists rotational symmetric form error of the center lens and it is due to the FTS stroke gain error. While the asymmetric form errors of the other lenses as shown in Figure 6 and 7 are due the complicated cutting system problems. We don’t need to calibrate the FTS stroke gain error anymore, because reducing the center lens form error by stroke gain adjustment would increase the form errors of other lenses.

The results show that the FTS diamond tool path with over cutting depth compensation could reduce the form error in aspherical lens array cutting effectively.

**CONCLUSION**

In this study the micro aspherical lens array with 60\(\mu\text{m}\) sag, 30mm basic radius and -1 conic...
coefficient was cut by Precitech FF705XG diamond turning machine with fast tool servo and measured by Panasonic UA3P-4. The measurement results show that the micro aspherical lens array fabrication using FTS with over cutting depth compensation could get acceptable form accuracy less than 0.3μm. It means the micro lens design will be more flexible on just the spherical surface.

FIGURE 5. Form accuracy of the center lens

FIGURE 6. Form accuracy of the upper lens

FIGURE 7. Form accuracy of the right lens

Acknowledgement
This work was supported by the National Science Council of the Executive Yuan, Republic of China under grant no. NSC 96-2221-E-492-009.

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