5-Axis Flex Track Drilling Systems on Complex Contours: Solutions for Position Control

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ABSTRACT

Previous Flex Track drilling systems move along two parallel tracks that conform to the contour of a work piece surface. Until recently, applications have been limited to relatively simple surfaces such as the cylindrical mid-body fuselage join of a commercial aircraft. Recent developments in the state of the art have introduced the 5-axis variant which is capable of precision drilling on complex contours. This paper presents solutions to two positioning challenges associated with this added functionality: the ability to align the spindle axis normal to an angled drilling surface while maintaining accuracy in tool-point position, the ability to maintain synced motion between dual drives on complex track profiles.

INTRODUCTION

Flex Tracks have seen increasing use in drilling and fastening applications on mid-body fuselage joins and wings. In designing the software on the 5-axis variant, commonality with previous Flex Tracks was maintained as much as possible. The purpose behind this was to provide the added functionality without requiring that current Flex Track operators and support staff learn a new paradigm before using the machine. This paper describes methods used to address the control challenges associated with a more complex machine, while keeping this goal in mind.

DESCRIPTION OF FLEX TRACK

A Flex Track is a mobile drilling platform that moves about on two flexible tracks held to the work piece using vacuum cups, as shown in Figure 1. The drill head moves back and forth between the tracks on its base plate. These two orthogonal axes define a surface representing the work envelope for numerically controlled drilling programs.

Two rotational axes have been added to the 5-axis Flex Track. These axes provide the capability to normalize the spindle axis relative to the work piece surface. The pivot points for these axes are offset from the work piece surface.

An offline programming package (OLP) in conjunction with the CAD model of the work piece is used to generate flat pattern drilling coordinates. This flat pattern is the starting point for positioning the Flex Track. The CAD model contains a virtual surface that represents the 2-dimensional work envelope of the machine once the tracks are mounted to the work piece; this is referred to as the inter-rail surface. The OLP projects all drilling points to the inter-rail surface and outputs the coordinates, as well as other hole-specific information, to an NC drilling program.

Once the machine is driven to position, single-sided clamping takes place prior to drilling. Servo-driven ball screws drive the clamp foot down to the work piece until a commanded force is achieved. The spindle assembly moves with the clamp foot which ensures that the tool position along the spindle axis will be maintained relative to the clamp surface. The clamp foot is gimbaled in order to sit flush on the surface of the work piece. Two important measurements are acquired during clamp up: the distance from the unclamped position to the work piece surface, and the angle of the clamp foot relative to the base plate. These measurements are used to improve tool-point accuracy and will be explained later.

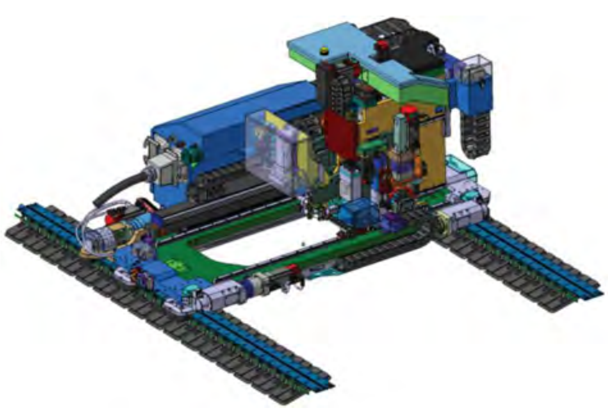

Figure 1. 5-Axis Flex Track

ACCURATE POSITIONING

Coordinate Systems

Two coordinate systems are used for controlling the 5-Axis Flex Track; these will be referred to as joint space and program space.

Joint space is defined by the Flex Track's physical axes which position the tool point and orient the spindle axis in three-dimensional space. The axis naming convention is shown in Figure 2. Joint space is defined in this paper as follows:

X_m - Linear motion tangent to the master rail trajectory

Y_m - Linear motion orthogonal to X_m intersecting the secondary rail trajectory

U_m - Linear motion along the clamp/spindle axis

B_m - Rotation of the spindle axis about Y_m

A_m - Rotation of the spindle axis about X_m, compounded with B_m

C_m - Rotation about the normal of the X_m-Y_m plane

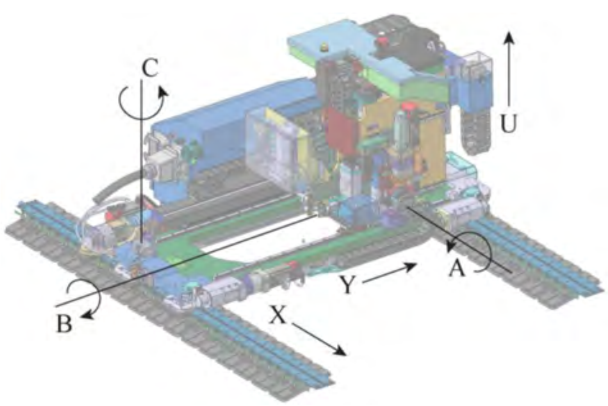

Figure 2. Axis naming convention.

Five of these axes are driven directly by the CNC. The sixth axis, C_m, is defined by relative motion between the X-axis master and slave drives, which manifests itself as a rotation about the normal of the X_m-Y_m plane. This will be discussed in the section Continuous C Squaring.

The definition of program space begins with the inter-rail surface, which is work piece specific. For every X position, a straight line can be drawn along the Y-axis from the master rail trajectory to the slave rail trajectory. This is the cross-section of the inter-rail surface at that X position, as shown in Figure 3. The inter-rail surface can then be defined as the collection of all these cross sections along the range of X.

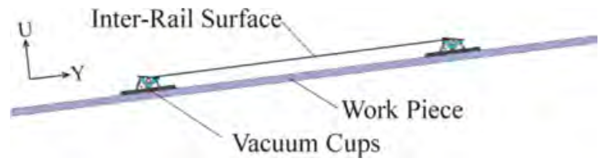

Figure 3. Cross section of the inter-rail surface, looking along the direction of the X axis.

The OLP projects the drilling locations from the three-dimensional CAD model of the work piece onto the two-dimensional inter-rail surface. Each projection is done normal to the inter-rail surface to generate the associated program coordinates X_p and Y_p. In addition, the OLP provides the distance of that projection and information about the angle of the projection relative the work piece normal. Program space coordinates are defined in this paper as follows:

X_p - Position on the inter-rail surface, along the master rail trajectory

Y_p - Position on the inter-rail surface, orthogonal to X_p

U_p - Position along the inter-rail surface normal

B_p - Angle between the work piece surface normal and the inter-rail surface normal about Yp

A_p - Angle between the work piece normal and the inter-rail surface normal about X_p (not compounded)

Datums

Locating the machine on the work piece, as well as adjusting for deviations from the CAD model, is done by datuming on known features such as holes and previously installed fasteners. The use of the flat pattern method for positioning allows for straightforward translation and rotation of local drilling patterns in 2 dimensions.

Two datums are used to define translation and rotation for a given local pattern. For the purpose of describing the transformation method, we will refer to these datums as K_1 (translation) and K_2 (rotation). A full part program can have any number of datum pairs used to define many local transformations.

Before moving to a programmed position, $\{X_p, Y_p\}$, the associated datums are located and stored in program space coordinates. Typically this is done using an onboard vision system. The nominal location of the datum $\{X_{Kn}, Y_{Kn}\}$ and the offset to the actual position $\{\Delta X_{Kn}, \Delta Y_{Kn}\}$ are stored, where n is the datum identifier. A compensated program coordinate for the drilling location is then computed using a standard translation and rotation transform in 2 dimensions:

$$X = X_{K1} + \Delta X_{K1} + (X_p - X_{K1})\cos(\theta) - (Y_p - Y_{K1})\sin(\theta) \tag{1}$$

$$Y = Y_{K1} + \Delta Y_{K1} + (X_p - X_{K1})\sin(\theta) + (Y_p - Y_{K1})\cos(\theta) \tag{2}$$

where θ is the rotation correction given by

$$\theta = tan^{-1}\left(\frac{(Y_{K2} + \Delta Y_{K2}) - (Y_{K1} + \Delta Y_{K1})}{(X_{K2} + \Delta X_{K2}) - (X_{K1} + \Delta X_{K1})}\right) - tan^{-1}\left(\frac{Y_{K2} - Y_{K1}}{X_{K2} - X_{K1}}\right) \tag{3}$$

Kinematics

Now that the local flat pattern has been adjusted by datuming, the spindle axis needs to be oriented with the surface normal. The goal is to rotate the tool about the drilling location on the surface of the work piece in order to maintain accurate positioning of the hole. Because the pivots for the A and B axis are offset from the work piece surface, X and Y positions in joint space will differ from their respective positions in program space. This adjustment can be computed using inverse kinematics.

We begin with the forward kinematics to transform a joint space coordinate $\{X_m, Y_m, U_m, A_m, B_m\}$ into a program space coordinate $\{X_p, Y_p, U_p, A_p, B_p\}$. The A_m pivot sits above the B_m axis and rotates with it. We define the A and B pivot heights above the inter-rail surface along U_p by d_A and d_B, respectively. Therefore, the sequence of transforms is given by

1. Translate by X_m, Y_m, and d_B
2. Rotate about the Y-axis by angle B_m
3. Translate along the rotated U-axis from the B pivot to the A pivot, a distance d_A-d_B
4. Rotate about the X-axis by angle A_m
5. Translate down to the work piece

After simplifying, the forward kinematics are given by

$$\begin{pmatrix} X_p \\ Y_p \\ U_p \end{pmatrix} = \begin{pmatrix} X_m + (\mathrm{d_A} - \mathrm{d_B})\sin B_m + (U_m - d_A)\cos A_m \sin B_m \\ Y_m - (U_m - d_A)\sin A_m \\ (\mathrm{d_A} - \mathrm{d_B})\cos \mathrm{B_m} + (U_m - d_A)\cos A_m \cos B_m + d_B \end{pmatrix} \tag{4}$$

The OLP provides B_p independently, not as a compounded angle with A_p. This was done by design to match the kinematics up with the output of the nose-piece normality sensors described in the next section. In order to achieve a target angle on the surface of the work piece the A-axis servo position, A_m, will need to be slightly different than A_p. By mapping the compounded machine angles onto the fixed program angles, the following equation can be derived:

$$\begin{pmatrix} A_m \\ B_m \end{pmatrix} = \begin{pmatrix} \tan^{-1}(\tan A_p \cos B_p) \\ B_p \end{pmatrix} \tag{5}$$

Now that we have B_m, we can solve Equation (4) for X_m and Y_m and simplify to get the inverse kinematics:

$$\begin{pmatrix} X_m \\ Y_m \end{pmatrix} = \begin{pmatrix} X_p + (d_B - U_p)\tan B_m \\ Y_p - ((d_B - U_p + (d_A - d_B)\cos B_m)\dfrac{\tan A_m}{\cos B_m} \end{pmatrix} \tag{6}$$

For small A and B angles, the inverse kinematics can be simplified by disregarding the fact that A_m is compounded. In this case, the program space A and B are approximated as equal to the joint space A and B, and position equations are given by

$$\begin{pmatrix} X_m \\ Y_m \end{pmatrix} = \begin{pmatrix} X_p + (d_B - U_p)\tan B_p \\ Y_p - (d_A - U_p)\tan A_p \end{pmatrix} \tag{7}$$

These simplified kinematics match the method used for single -angle normalization on previous Flex Tracks at the cost of accuracy. Prior to using this method, a simulation should be run to determine if the errors in position and orientation are acceptable for the given geometry of the work piece.

Normalization

The CNC will drive the X and Y axes to the computed joint space coordinate and clamp up. In real world applications, the work piece surface geometry deviates from nominal, especially under the load of the clamp foot. Therefore, adjustments are made to ensure accurate position and orientation based on measurements taken during clamp-up.

Tool orientation (normality) relative to the surface is measured using three potentiometers integrated into a nosepiece with a gimbaled clamp foot as shown in Figure 4. If the measurements are outside of a configurable tolerance from the associated program values the machine will unclamp, adjust the target angles, rerun the inverse kinematics to move to a new joint space coordinate, and reclamp. This is done iteratively if necessary, but will only require one cycle if the machine is well calibrated for the tolerances given.

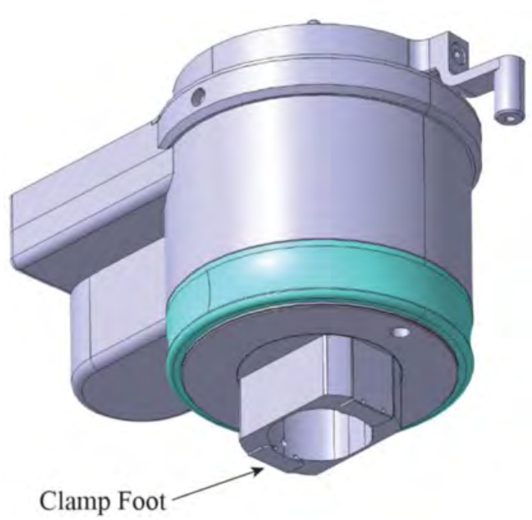

Figure 4. Nosepiece with gimbaled clamp foot.

Clamp depth is measured using feedback from the clamp servo encoder. If there is sufficient error between the clamp depth measurement and the OLP value, the kinematics will be incorrect resulting in X and Y positioning error. Therefore, the machine will unclamp and adjust its joint space coordinate based on the measured value.

CONTINUOUS C SQUARING

An important difference between a Flex Track that operates on simple work pieces and a 5-Axis Flex Track is in the way that the X axis master and slave servos are synced. For surfaces like the mid-body fuselage of a commercial aircraft, the master and slave rails follow nearly identical trajectories in space offset along the machine's Y axis. For these surfaces, the CNC's built in sync function is used. For every inch moved by the master servo, the slave servo also moves an inch. Small errors in C accrue over long distances, but this can be mitigated by performing a squaring move once the master axis is in position.

The 5-Axis Flex Track is designed to handle rail trajectories of more complex shapes such as aft-body joins: a tapered cylinder with varying radii of curvature across the work envelope. Using the standard sync function will result in large errors in C over relatively short distances in X. Therefore, a method for squaring C while the X axis is moving was developed.

Proportional control within the programmable logic controller was found to be sufficient. First, an estimate of the appropriate feedrate for the slave axis is computed based on a measurement of the master axis velocity. This feed-forward component of the controller can be scaled for tapered barrel work pieces where the average radius of curvature of the slave axis differs from that of the master; we will call this scale factor K_f. Feedback from the C-axis encoder is then used to modulate the feedrate of the slave servo while in motion. Disturbances include local variation in radii of curvature and system delays associated with acquiring the master axis velocity and formatting it into a feedrate modulation. A block diagram is shown in Figure 5.

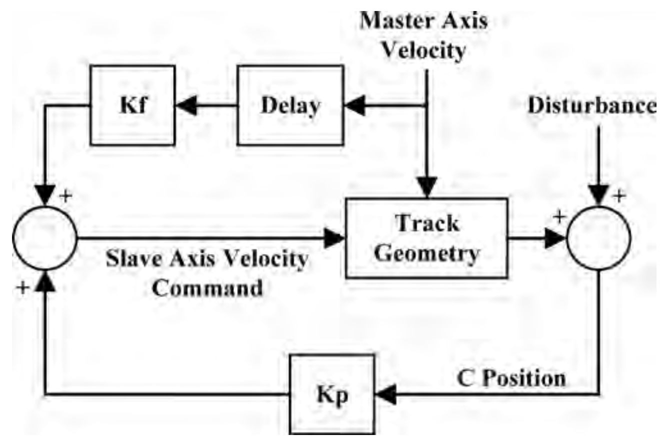

Figure 5. Block diagram of the control loop for continuous C-squaring, with feedback gain given by K_p.

CONCLUSION

As Flex Track systems become a viable drilling platform for more complex surfaces, the use of inverse kinematics becomes important to ensure positioning accuracy. Furthermore, control design may be required to deviate from plug-and-play style control algorithms such as built in axis synchronization. This paper serves as a baseline for further development in these areas.

CONTACT INFORMATION

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ACCRONYMS

CAD - Computer Aided Design

OLP - Offline Programing Package

CNC - Computer Numerical Control

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