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Implementation of Non-Contact Drives into a High-Rail, 7-Axis, AFP Motion Platform

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ABSTRACT

Traditionally, automated fiber placement (AFP) motion platforms use rack and pinion drive trains coupled through a gearbox to a rotary motor. Extensive use of non-contact linear motors on a new AFP motion platform produces a quiet, low-maintenance system without sacrificing precision. A high-rail gantry arrangement allows dynamic performance improvements to machine acceleration and speed, while lowering power consumption costs and capital expenses. The seventh axis incorporated into the machine arrangement effectively produces an effective "five sides of a cube" work envelope, permitting complex spar and panel fabrication.

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INTRODUCTION

AFP motion platforms have historically used rotary motors coupled with gear reducers and rack and pinion drive trains. Installing and setting precision rack and pinion is a difficult and time consuming task. The lubrication required to maintain these systems also must be contained and separated from the clean room environment used to manufacture carbon fiber components.

Linear motors offer an attractive alternative to rack and pinion drive systems. They are easier to install, and do not have moving parts that must be maintained and replaced with repeated wear. Linear motors require no lubrication, limiting lubrication on the drive to just the bearing cars. This makes isolating grease and oil within a clean room environment a much easier task.

Elevating the X-axis from the factory floor has many advantages as well. "High rail" gantry designs further isolate grease from production parts. "High rail" designs also are safer by separating many moving machine parts from operators. This paper describes these system advantages over a traditionally driven "high leg" gantry style AFP motion platform.

"HIGH RAIL" GANTRY DESIGN

A major design challenge when building an AFP machine for large commercial aircraft programs is creating a working envelope large enough for the parts while maintaining dynamic performance and accuracy required for quality layups and high throughput. A gantry type machine is favorable for many part families including: wing covers, spars, and fuselage sections. However, as the size of these parts increase, the height under the bridge of the gantry must also increase. In a traditional "high leg" gantry, this height increase requires longer legs with a longer footprint, which leads to higher machine mass, larger drives, and a less rigid machine.

A solution to this problem is a "high rail" gantry. In this arrangement the X beds, which would otherwise be on or below floor level, are located on top of concrete plinths roughly as high as the gantry bridge. This eliminates the mass of the "high leg" gantry legs and positions the X drives closer to the center of gravity of the system. This also eliminates trip hazards associated with floor-level beds, or costly pass through way covers required with below grade beds, which also prevent heavy carts and tools from rolling into the cell.

It is true that the foundation requirements for a "high rail" gantry are higher than they would be for a "high leg" gantry, but this cost is offset by a reduction in machine price, along with lower operating costs for moving less overall machine mass. When looking at the total cost of a machine cell, it is likely that a "high rail" gantry will cost less than a "high leg" system with the same bridge height.

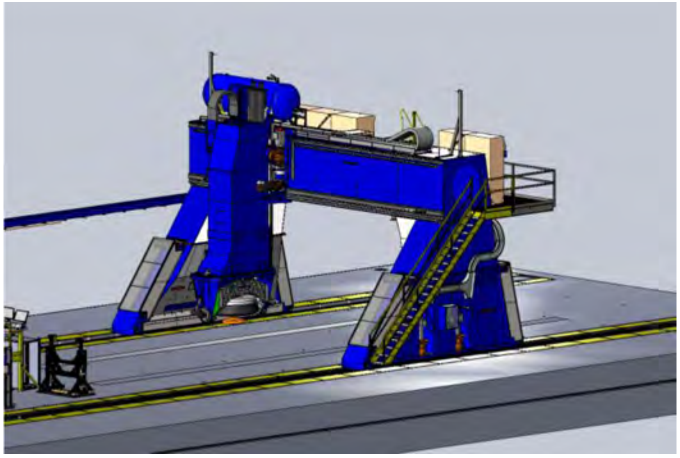

Figure 1. A traditional "high leg" gantry AFP positioner increases moving mass to allow for a large working envelope.

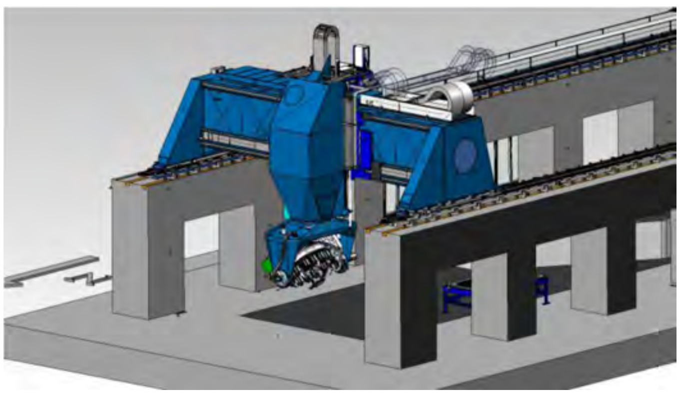

Figure 2. A "high rail" gantry system eliminates the need for heavy structural legs.

Figure 3. Concrete plinths provide a natural barrier to the work zone, reducing risk of harm to personnel.

Improved safety is another major advantage of the "high rail" design in a production environment. The concrete plinths along X create their own "stay out zone" which is much easier to enforce with physical barriers and laser curtains. By elevating the X drives, the possibility of personnel strikes with the X axis is all but eliminated, as is the requirement for way covers over the beds. This also keeps people and tools safely away from the very strong permanent magnets used by the linear motors. Magnetic attraction to ferrous parts and tools creates a potential risk for the linear drives. Placing the drives on top of the plinths helps to mitigate this risk.

MAJOR AXIS LINEAR MOTORS

Non-contact linear motors for the X, Y, and Z axes were used in place of traditional rotary motors, gearboxes, pinions, and rack typically used on AFP machines. Rack and pinion lubrication systems are eliminated as a result. This greatly reduces the risk of part contamination from grease.

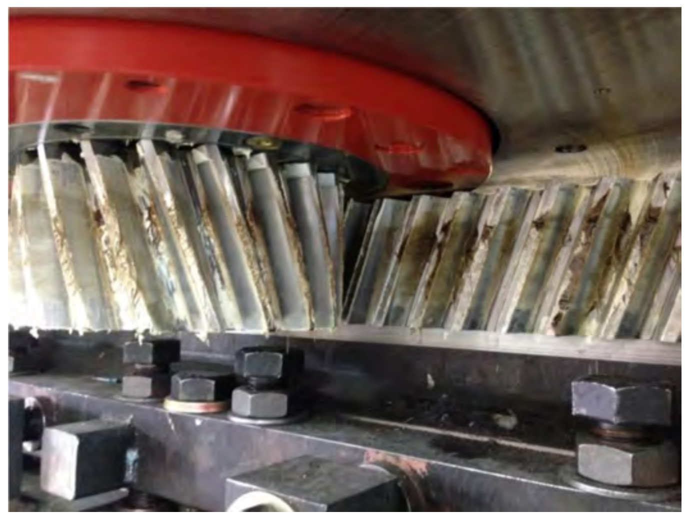

Figure 4. Rack and pinion drives require grease that must be isolated from the clean room environment.

While it is possible to run linear motors with no cooling or forced air cooling, the power and duty cycle of a linear motor increase significantly with chilled water cooling. This necessitates the use of a water chiller, along with a pump and distribution network for the coolant. In areas where freezing is not a concern, tap water with an anti-corrosive additive can be used. The temperature of the fluid is typically between 70F and 100F. Using this non-toxic fluid at relatively low temperatures prevents the possibility of burns in the event of a leak.

The attraction force between the magnets and linear motors can be on the order of 45kN. The machine structure must be rigid to react this load. Typically additional linear rail and bearing cars are added adjacent to the magnets and linear motors, respectively, to localize the force reaction. The installation requirements of the magnets and additional rail are significantly less time consuming than setting precision rack and pinion backlash, saving valuable installation time.

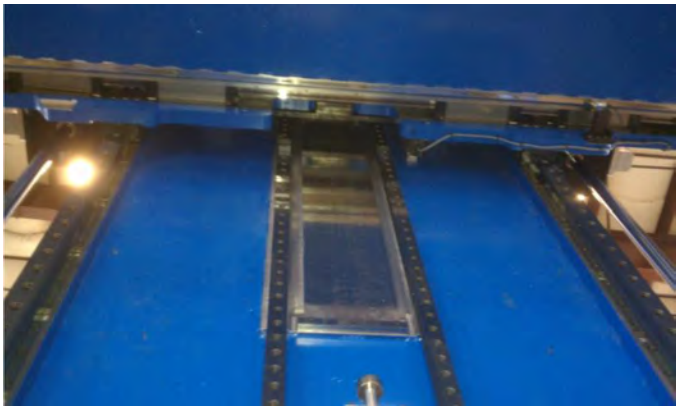

Figure 5. Attraction forces are reacted with linear rail locally around magnet plates.

Non-contact drives require little to no maintenance. With proper cooling and prevention of FOD ingress onto the magnets, linear motors should operate for the life of the machine. Without any moving parts, these drive systems have inherently fewer potential points of failure.

Another benefit of linear motors is their quiet operation. Rack and pinion drive systems, coupled with gear trains, create sound in excess of 70 dB. In comparison, linear motors on this “high rail” gantry machine are nearly silent. In fact, the motors are so quiet that linear bearing car selection is important to reduce the sound of rolling elements falling in the race way. This machine uses THK caged rollers due to their quiet operation.

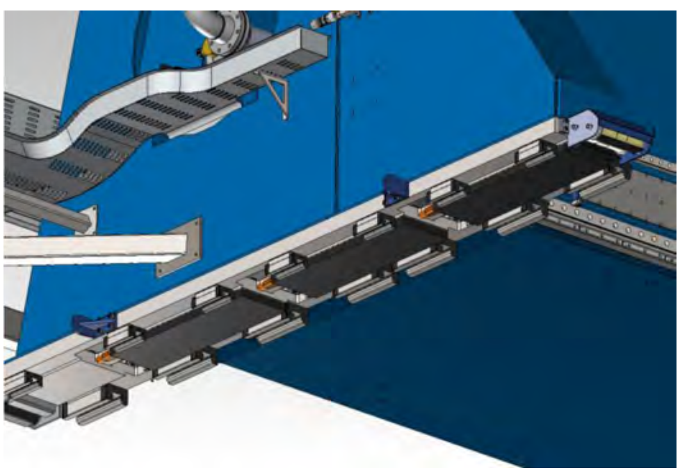

Figure 6. Multiple linear motors are used on the same axis to improve machine top speed and acceleration.

Rack and pinion drives have a number of drawbacks that cannot be avoided. First, to prevent backlash from affecting the accuracy of a rack and pinion driven machine, either two drive pinions or a split pinion is required. These systems which address backlash are both expensive and inefficient. Linear motors have no backlash, and do not require any preload. The second drawback of rack and pinion drives is speed. Rotary motors are speed limited, and, depending on your machine mass and gear train, it is possible to reach that maximum speed during production. When this occurs with a rotary motor, gear trains may be altered to have higher top speeds or higher accelerations, but not both. Linear motors have a top speed far above what an AFP machine would use (3 m/s), and multiple motors can be installed on one axis. So, if higher acceleration is required, additional linear motors may be added to the axis.

CONTROLS CONFIGURATION

The Aurora AFP Machine uses a Fanuc 30i-B CNC. All the axes controlled with servo motors use standard Fanuc configurations. For the purpose of this paper Fanuc synchronous control is analogous with position copy and Fanuc tandem control is analogous with torque copy. Both axes B and C each use a single servo motor with the motor's encoder being the primary feedback. The A-axis is controlled with two synced servo motors. The A-axis uses standard Fanuc synchronous control with primary feedback coming from the master motor's encoder.

The Z-axis consists of two linear motors with synchronized position commands and shared position feedback. Primary feedback comes from a Renishaw Resolute Absolute Scale. The scale's output is connected to the master Z motor which copies its position to the slave Z motor (the slave motor has no physical feedback) [2]. Both the X and Y axes use non-standard Fanuc configurations (X-axis shown in Figure 7 and Y-axis shown in Figure 8) in order to achieve the desired capability.

The X-axis is split into two groups of linear motor triplets (the master side and the slave side). The master side motors are referred to as X_M, X_{M2}, and X_{M3}. Whereas the slave side motors are similarly referred to as X_S, X_{S2}, and X_{S3}. Both X_M and X_S receive primary feedback from incremental scales. No physical feedback is provided to the remaining X-axis linear motors, they receive their position and torque commands from the X_M or X_S motors on their respective side. All motors are synced to the X_M motor. Standard Fanuc torque tandem control could not be used because tandem

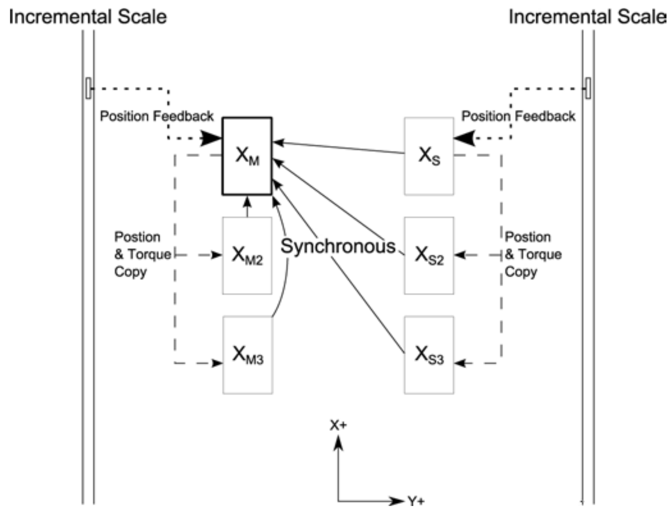

Figure 7. X-axis Controls Configuration

control requires pairs of motors (and does not accept triplets) [3].

Rather than create a dummy motor on both the master and slave side it was decided to proceed with position synchronous control. Standard position synchronous Fanuc control only allows for the synching procedure to be performed on two motors. A synching procedure performed with more than two motors results in failure. Because of this limitation only the X_S motor was used to perform the synching procedure with the X_M motor. The remaining four motors were not used in the syncing procedure. With this configuration only the X_M and X_S motors could perform the standard Fanuc homing routine. The remaining four motors were commanded to be homed at any arbitrary position rather than perform a homing routine. The Fanuc routine shifts the position of the motors being homed to an operator's specified position in the machine cell. Since only the X_M and X_S motors can perform homing they are the only motors where this shift is applied.

This resulted in X_M and X_S sharing the same and accurate position, but the remaining four motors have meaningless positions. To mitigate this problem the in-position parameter for each of the remaining four motors is set to an integer larger than the entire length of the incremental scale. An error occurs if the position error of any motor becomes larger than the in-position parameter for that motor. With the in-position parameter exceeding the length of the scale, this error cannot occur. The torque commands copied from the X_M and X_S motors insures desired performance for the remaining four motors.

In contrast to the X-axis, the Y-axis has only one set of linear motor triplets rather than two sets (see Figure 8). Otherwise, this axis is configured exactly the same as the X-axis. The Y_M motor receives feedback from an absolute scale. The same position and torque is copied from the Y_M motor to the Y_2 and Y_3 motors. Once again Fanuc torque tandem control cannot be used because of the triplets, thus the same X-axis position synchronous control is used. Only the Y_M motor can perform the Fanuc homing routine, resulting in inaccurate positions with very large in-position parameter settings for both Y_2 and Y_3. This potential error is avoided through the same approach that is deployed on the X-axis.

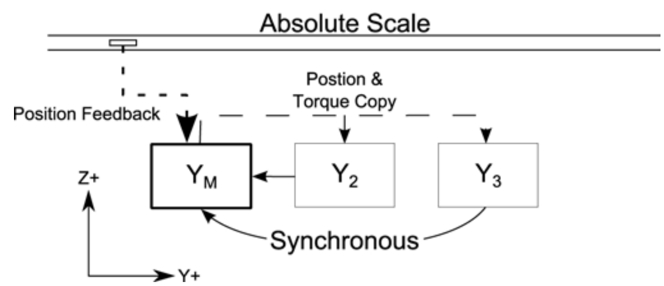

Figure 8. Y-Axis Controls Configuration

Optical vs. Magnetic Linear Scales

Currently Fanuc requires that scales paired with Fanuc linear motors must have a signal pitch smaller than 200 μm. This requirement, paired with the required extents of travel and desire for absolute scales led Electroimpact to choose optical scales over magnetic. Renishaw Resolute optical absolute scales were applied to the Y and Z axes. Because the length of X travel exceeds the maximum length of these scales, the X axis uses an incremental optical scale with a single reference mark.

7TH AXIS KINEMATICS

The ABC axis arrangement on this machine follows a traditional AFP arrangement with the compaction roller with the C-axis providing tow steering while A and B axes provide compaction axis orientation [1]. The axis packaging on this particular machine limits A-axis rotation to +/− 90 degrees, B rotation to +/− 10 degrees, while the C-axis maintains continuous rotational motion. While this arrangement is adequate to manufacture many spars and panels, the limit of B rotation prevents fabrication of many other complex parts.

Repackaging a B-axis with +/− 90 degrees rotation would provide true "five sides of a cube" work envelope. However, its integration into the machine design would add considerable mass, reducing overall machine performance. To achieve an effective "five sides of a cube" work envelope, a C-prime axis is installed between the A-axis yoke and Z-ram. This +/− 105 degree C-prime axis adds minimal mass to the machine architecture while allowing an effective +/− 90 degree B-axis rotation. Providing a motion platform with "five sides of a cube" capabilities allows for the manufacture of complex spar and panel parts.

Figure 9. By utilizing a 210 degree range of motion, a C-prime axis effectively allows for 180 degrees of B-axis rotation.

COUNTERBALANCE

Driving the vertical axis (Z) of a gantry machine with linear motors poses some interesting design challenges. Chief among these is the counterbalance system. In a traditional rack and pinion vertical axis, the counterbalance is set to something slightly less than the vertical mass so that the pinion would always be loaded in the same direction regardless of acceleration or position. The work to hold the axis is still minimized.

Because there is no backlash associated with linear motors, the counterbalance can be set to 100% of the vertical mass, theoretically minimizing the work done by the motors when holding position. For this machine, two pneumatic cylinders along with a large accumulator are used as a large air spring. The purpose of the accumulator is to minimize the change in spring force over the length of the axis due to the changing volume in the air cylinders.

Figure 10. two large pneumatic cylinders work in conjunction with a large accumulator to counterbalance 100% of the mass of the vertical z-axis.

SUMMARY/CONCLUSIONS

A "high rail" gantry design has many advantages over other machine architectures including cost, safety, and machine performance. Linear motors on XYZ require more rails and a chiller, but reduce noise and installation time, and can increase machine performance. Perhaps most importantly for AFP applications, the possibility of rack grease contaminating a part is eliminated. Maintenance is significantly reduced through use of a linear motor over a traditional rack and pinion drive.

Seventh axis architecture delivers a machine with effective "five sides of a cube" capabilities. This axis arrangement allows for fabrication of complex spars and panels with minimal effect to machine mass or performance.

The advantages a "high rail" system can deliver to a production facility must be closely considered when procuring new equipment. Although the initial foundation costs can be higher than pits or floor level beds, those costs are offset by machine pricing and increased dynamic performance.

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DEFINITIONS

AFP - Automated Fiber Placement

CFRP - Carbon Fiber Reinforced Plastic

CNC - Computer Numerical Control

FOD - Foreign Object Debris

APPENDIX

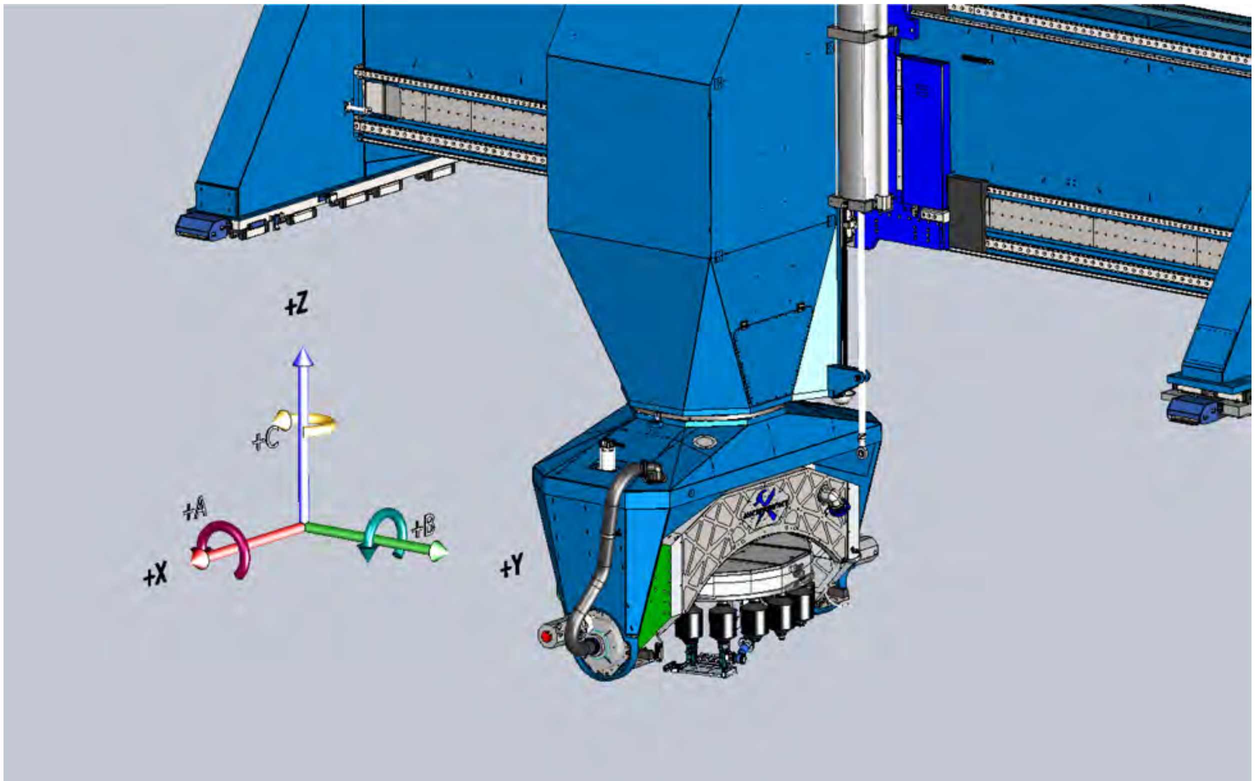

Figure 11. Machine axis coordinates.