LANSCE WIRE SCANNING DIAGNOSTICS DEVICE MECHANICAL DESIGN

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INTRODUCTION

The Los Alamos Neutron Science Center (LANSCE) is one of the major experimental science facilities at the Los Alamos National Laboratory (LANL). The core of LANSCE's work lies in the operation of a powerful linear accelerator, which accelerates protons up to 84% the speed of light. These protons are used for a variety of purposes, including materials testing, weapons research and isotopes production. To assist in guiding the proton beam, a series of over one hundred wire scanners are used to measure the beam profile at various locations along the half-mile length of the particle accelerator. A wire scanner is an electro-mechanical device that moves a set of wires through a particle beam and measures the secondary emissions of electrons from the resulting beam-wire interaction to obtain beam intensity information. When supplemented with data from a position sensor, this information is used to determine the cross-sectional profile of the beam. This measurement allows beam operators to adjust parameters such as acceleration, beam steering, and focus to ensure that the beam reaches its destination as effectively as possible. Some of the current wire scanners are nearly forty years old and are becoming obsolete. The problem with current wire scanners comes in the difficulty of maintenance and reliability. The designs of these wire scanners vary making it difficult to keep spare parts that would work on all designs. Also many of the components are custom built or out-dated technology and are no longer in production.

DESIGN CRITERIA

The first design criterion is that the wire scanner should be constructed with as many commercially available off-the-shelf components as possible. This will facilitate having spare parts that can fit multiple wire scanners. This is similar to the wire scanner design of the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) wire scanner. The second criterion is that the wire scanner should be capable of 1mm movements at 4Hz (1mm in 250ms) with a triangular velocity profile as illustrated in Figure 1. Notice that for the area under the curve to be 1mm, the peak velocity must be 8mm/s half way through the motion. This yields an acceleration of $64 mm/s^2$ (Note: $1g = 9807 mm/s^2$). Third, the position of the wires at the end of the "fork" must be known within ±1mm with respect to an external monument. Also, the repeatability of the system must be within ±0.1mm. Fourth, the motor must be powered off while taking a measurement at each bin location. Lastly, the wire scanner should be designed to accommodate as many existing beam structures as possible.

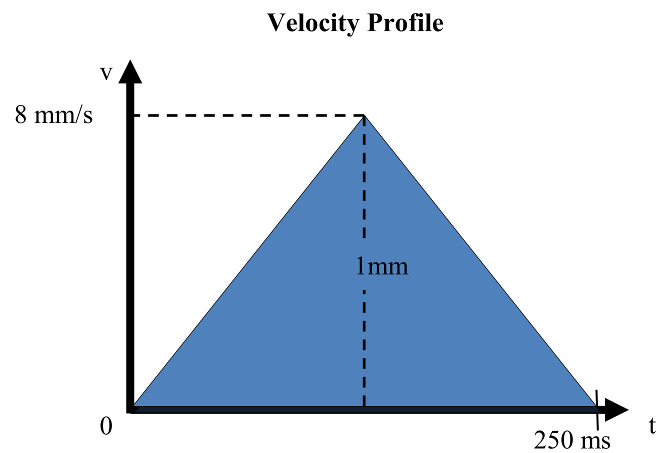

Figure 1: Velocity profile for the wire scanner.

MECHANICAL DESIGN

As mentioned above, the first design criterion resembles that used by ORNL and likewise does so the mechanical design. Figure 2 shows the ORNL wire scanner design.

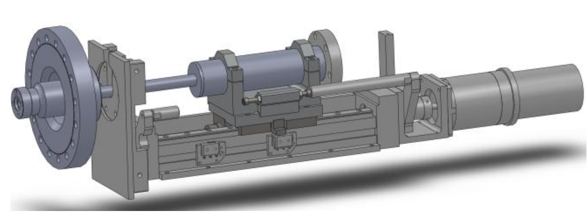

Figure 2: ORNL SNS wire scanner design.

The ORNL SNS wire scanner design has been modified to fit our current beam structures and our design specifications. Figure 3 shows the LANSCE future wire scanner design.

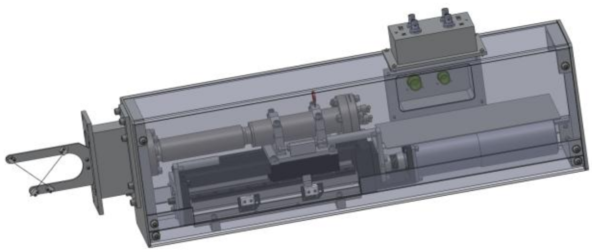

Figure 3: LANSCE wire scanner.

The first difference to notice is the mounting interface between the wire scanner and the beam structures; ORNL uses a circular pattern while LANSCE uses a rectangular pattern. Second, ORNL uses a one-piece rectangular frame with removable side and top panels while the LANSCE wire scanner design is a two-piece, top and bottom, frame with removable front and rear plates. The LANSCE wire scanner can be broken down into 6 sub components or sub assemblies: frame, drive system, arm assembly, fork, accessories, and motor. These will be further discussed in the following sections.

Frame

The frame provides structural support to the wire scanner. Additionally, the frame has been designed to house all of the wire scanner's components internally and thus protecting them from dust and debris. As mentioned above, the frame is composed of four components: the front plate, back plate, top of the frame, and bottom of the frame; all made from 6061 aluminum alloy. The front plate has three sets of tapped holes; the outer holes are used to mount the garage to the wire scanner. The inner set of holes is used to mount the bellows and thus creating a vacuum seal. The holes on the sides are used to hold together the top and bottom of the frame. The back plate also has a set of tapped holes to increase the rigidity of the system. The top and bottom of the frame have been designed in such a way that the top of the frame can be removed to gain access to the internal components while maintaining the bottom of the frame in place.

Drive System

The drive system converts the rotational input of the motor into linear motion. A Lintech 100-series linear stage with a 10-mm-lead ball screw and 6 inches of available travel was selected. It comes fully assembled with a NEMA 23 motor mount and motor coupling. The slide table travels on two rails with two linear bearings per rail. Each bearing has a dynamic load capacity of 775 lbs rated for 2 million inches of travel; the table is estimated to only travel 36,000 inches in 20 years, with a load of 7 lbs at most. The maximum acceleration of these bearings is 19.6 m/s² (2 g's). Some additional features are two mounts for limit switches and a cover plate to protect the ball screw from dust and debris.

Arm Assembly

The arm assembly acts as support for the fork as well as a vacuum boundary with an electrical feedthrough for the signal wires. The fork adapter has two threaded holes where the fork assembly bolts onto. The arm is a hollow ½ inch stainless steel tube, this allows for the signal wires from the fork to travel through it and gain access to the electrical feedthrough. This is welded to the fork adapter and the tube bushing. The bellows allows motion while maintaining vacuum on the inside. This is also welded to the tube bushing as well as to a Conflat (CF) 2.75 flange that bolts onto the front plate. The bellows and flange assembly is provided by Metal Flex Welded Bellows Inc. part number 13783AA-10. The larger tube in this assembly acts as the sole support for this assembly. On one end it is welded to the tube bushing, on the other it is welded to a CF 2.75 flange. This tube is supported by a carriage and clamp assembly that mounts onto the linear stage. Finally, the electrical feedthrough is composed of 4 double-ended SMA connectors built into a CF 2.75 flange. This allows for the signal to travel from the wires on the fork to the outside while maintaining vacuum on the inside. This feedthrough is from Accu-Glass Products, Inc. Model Number 2SMA-GS4-275.

Fork

The fork assembly is designed such that two wires, positioned perpendicular from each other, act as X and Y beam profile indicators when mounted at ±45° from the horizontal. This assembly allows for the current to travel from the wires through the arm and exit through the electrical feedthrough. The fork and fork bracket are made from aluminum while the wire mounts are made from macor. The wire itself is typically 0.1mm diameter of tungsten, silicon carbide, or carbon fibers.

Accessories

Accessories for the wire scanner include the mounting interface, limit switches, hard stops, carriage, connectors, and cable guard. The mounting interface supplies extra room the fork when it is fully retracted. The limit switches indicate the system when it has reached it inward and outward limit. The hard stops act as protection in the case that the wire scanner does not stop at the in or out limit switch positions. The carriage is the mounting point for the arm assembly and moves with the linear stage. The connectors allow for both the retrieval of the current from the signal wires as well as connections for the motor, resolver, and limit switches. Lastly, the cable guard protects the signal cables from getting tangled with any other component(s).

Mounting Interface

As mentioned above, the mounting interface serves as extra room for the fork to retrieve into away from the beam line. Additionally, the mounting interface, serves as the mounting interface between the beam structure and the rest of the wire scanner. This component is a solid rectangular piece of aluminum 6061 with two flanges on its ends. The flange that interfaces with the beam structure is flat while the one that interfaces with the rest of the wire scanner has a groove for a 0.040in diameter aluminum 1100 wire seal.

Limit switches

For this design we will be using three limit switches, one for the in-limit and two on the out-limit. On the out-limit, one of the switches lets the operators know that the wire scanner is ready to perform while the second limit switch simply indicates when the wire scanner has fully retrieved from the beam line. The first out-limit switch to engage is the one that indicates that the wire scanner is fully retrieved, the other lets the operators know that the wire scanner is ready to run or if it is done.

Hard Stops

The hard stops act as mechanical precautions in the case that the stage does not stop when the trigger engages the limit switches. These hard stops mainly protect the fork from over travel into the beam structure. Additionally, it protects the bellows from over extending or over compressing which may cause tearing and leaks.

Carriage

The purpose of the carriage is to hold the arm assembly to move with the linear stage. Additionally, this carriage has two tapped holes for screws to act as the impacting surface with the hard stops in the case of over travel.

Connectors

Connectors are needed to transfer signals from the wires intercepting the beam and also to interface with the motor, resolver, and limit switches. For the signal wires, four BNC bulkhead connectors are used in this design. These four connectors mount to the mounting case via D-shaped holes. The mounting case is engraved with indications of which connections belong to which set of wires depending on the orientation that the wire scanner is mounted. The 90° wires indicate the X-profile of the beam while the 0° wires indicate the Y-profile of the beam. For the motor, resolver, and limit switches, two MS connectors are needed. One is a 19-pin connector and the other a 10-pin connector. The motor requires 8 wires which would go on the 10-pin connector. The limit switches require a total of 9 wires and the resolver requires 6; these 15 wires would go onto the 19-pin connector. The mounting cases for these connectors are made from aluminum-6061 stock machined to specifications and bolted to the top and side of the frame.

Cable Guard

The cable guard is designed to protect the signal wires that run from the electrical vacuum feedthrough to the BNC connectors. This cable guard allows for the wires to rest on it while the actuator is in its fully retracted position thus protecting them from getting tangled on any other component and at the same time preventing contact with the motor which may be hot. The cable guard is manufactured with 14-gauge aluminum sheet metal bent at 90 degrees and mounts along with the out-limit hard stop mount and motor mount onto the linear stage.

Motor

Because of the velocity requirements for the movements made by the wire scanner, the motor had to be sized correctly in order to achieve the specifications. In the process of sizing the motor we compared two types of motors; stepper and servo motors. Both motors have their advantages over the other and these are discussed in this section of this document. The motors being compared are from Empire Magnetics Inc. (EMI) since it is one of the few manufacturers that offer radiation-hardened motors.

As you will see in Figure 4 and Figure 5, servo motors have more torque available than stepper motors for the same rotational speed. As shown in Figure 1, a 1 mm movement in 250 ms would require a maximum velocity of 8 mm/sec assuming a triangular velocity profile. If we use a 10 mm lead ball screw this speed translates to 0.8 revolutions per second (RPS) or 0.048 kilo revolutions per minute (krpm).

Figure 4 shows that at this velocity the stepper motor has an available 400 oz-in of torque. Figure 5 shows that at this velocity the servo motor has an available 40 in-lbs of torque which convert to 640 oz-in. Additionally, servo motors have lower rotor inertia than a stepper motor for motors of the same frame size. An advantage over the servo motor is that the stepper motor has a detent torque that helps prevent back driving of the system. Since the wire scanner is mounted in a vacuum environment at a ±45° angle from the horizontal axis, it is prone to back drive due to gravity and vacuum forces. The equations below were used to correctly size the motors.

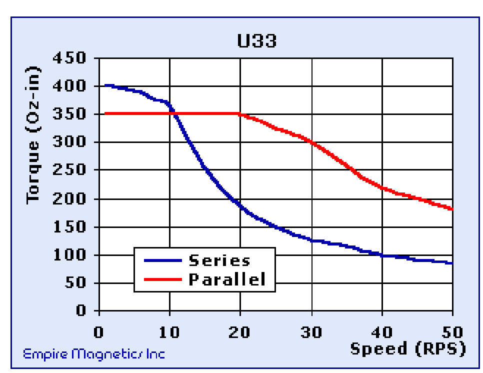

Figure 4: EMI U33 stepper motor speed vs. torque curves.

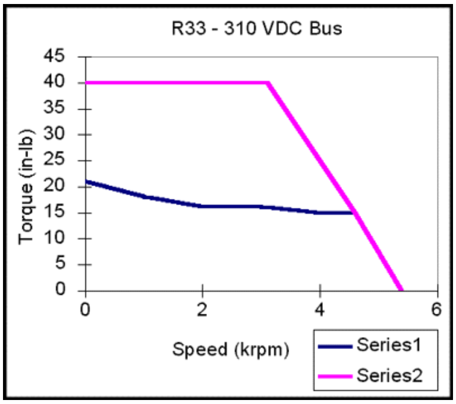

Figure 5: EMI R33 servo motor speed vs. torque curves.

In order to determine if the desired velocity will be reached, the torque required to perform such action must be calculated. To do so, the following equations have been used. The torque required for this task is composed of three parts, the torque to overcome axial loads, the torque to overcome frictional loads, and the torque needed to accelerate the ball screw to the desired velocity. The axial loads in this case would be the vacuum force, gravitational force, and the spring force due to the bellows.

$$\tau = \tau_{friction} + \tau_{axial} + \tau_{accelerate}$$

$$\tau_{friction} = \frac{\mu W sin(45) \times Lead}{2\pi e}$$

$$\tau_{axial} = \frac{(F_{vac} + W cos45 + F_{spring}) \times Lead}{2\pi e}$$

$$F_{vac} = P_{atm} A$$

$$F_{spring} = kx$$

$$\tau_{accelerate} = (J_{load} + J_{screw} + J_{motor}) \frac{\omega}{t}$$

$$J_{load} = \frac{W}{g(\frac{2\pi}{Lead})^2}$$

$$J_{screw} = \frac{\pi r^4 \times L \times \rho}{2g}$$

$$\omega = \frac{2\pi v}{Lead}$$

Table 1 shows the given values for the variables on the equations listed above. From these values and these equations the following results have been tabulated to compare stepper motors with servo motors and different size motors in each of those classes. All of the motors listed are from Empire Magnetics Inc. (EMI).

Table 1: Given values

μ	Friction coefficient between ball screw and nut = 0.01
W	Load carried by linear stage = 7lbs
Lead	Linear distance per revolutions of the ball screw = 10mm/rev
e	Efficiency of the screw = 90%
P_{atm}	Atmospheric pressure (at 7,200 ft elevation) = 78.19 kPa
A	Area where vacuum pressure is applied = 4.383 x 10^{-4} m²
k	Spring Coefficient = 2.5 lbf/in
X	Bellows compression distance (stroke length) = 3.5 in
J	Moment of Inertia (J_{motor} depends on motor)
ω	Maximum angular velocity = 5.03 rad/s
t	Time to reach peak velocity on triangular velocity profile = 125ms
r	Ball screw radius = 8mm
L	Length of ball screw = 330mm
ρ	Density of ball screw (stainless steel) = 8 g/cm^3
v	Maximum linear velocity = 8mm/s

Table 2 lists the EMI stepper motors with their respective required and available torque values.

Table 2: Stepper motor torques

Motor Model#	Torque Available in Series (oz-in)	Torque Available in Parallel (oz-in)	Total Torque Required (oz-in)	Ratio of Torque Available/ Required
U43	1545	2278	12.47	123.92
U42	1161	774	10.18	114.08
U41	385	308	7.89	48.82
U33	443	402	6.67	66.44
U32	294	247	6.29	46.72
U31	143	161	5.96	24.00
U23	146	90	5.78	25.27
U22	98	49	5.73	17.11
U21	55	52	5.64	9.74

Table 3 lists the EMI servo motors with their respective required and available torque values. From Tables 2 & 3, all the motors, both stepper and servo, have enough torque available to complete the required task of 1mm in 0.250ms. Because all of these motors have enough torque, the more desirable are the smaller motors since this simplifies the overall design of the wire scanner. This led us to concentrate on stepper motors U21-23 and servo motors R32-34.

Table 3: Servo motor torques

Motor Model#	Continuous Torque Available (oz-in)	Intermittent Torque Available (oz-in)	Total Torque Required (oz-in)	Ratio of Torque Available/ Required
R32	224	480	6.00	31.33
R33	336	640	6.12	44.43
R34	432	960	6.24	66.69
R43	560	1120	6.87	81.53
R45	768	1680	7.38	104.03
R46	960	2240	7.90	121.55
R63	1024	2400	10.23	100.13
R65	1840	3840	12.80	143.75
R67	2480	2480	15.37	161.32

An additional consideration that needs to be taken is the possibility of the system back driving. In this system, when powered off, vacuum forces as well as gravitational forces induce a torque on the ball screw. If this torque is greater than the frictional torque between the screw and nut, then the screw will rotate causing unwanted movement of the system. This affects servo motors differently than stepper motors due to the servo's free spinning rotors and the stepper's detent torque. A stepper motor's detent torque can be enough to prevent back drive. From the equations above, the total back driving torque is 11.417 oz-in. Table 4 lists the stepper motors in the NEMA 23 frame from EMI and their respective detent torques.

Table 4: Stepper motor detent torques

Stepper Motor	Detent Torque (oz-in)
U21	6
U22	15
U23	21

From this table we can see that the U22 and U23 motors have enough torque to prevent back drive. However, the U22 only has 31% more torque than the back driving torque. For reliability purposes, the U23 is a much better choice with almost twice the torque required to prevent back driving of the system. Servo motors provide more torque than the stepper motors; however they have a free spinning rotor that does not prevent back driving. If a servo motor were to be used in this system, a brake would need to be implemented adding complexity to the system. The chosen stepper motor has over 20 times the torque required and therefore it is the chosen motor for this design.

CONCLUSION

This wire scanner is designed with the intent to perform all of its duties as well as possible while maintaining the design simple and easy to maintain. Most of the main components are available off the shelf which makes replacing parts easier and faster. Current wire scanners along the linear accelerator (linac) consist of many custom parts and vary in design. Another goal of this project is to standardize the design of the wire scanners in order to have interchangeable parts that fit wire scanners at different locations along the linac. By doing so, we are able to have spare parts that can be used on different wire scanners as opposed to just a handful.