Square One Systems Design
An Integrated Support and Alignment System for Large ILC Lattice Elements
No. SQR1-068-R1

System Requirements: The two primary goals of the Phase I effort were to demonstrate the continued functionality of the Tri-Sphere concept when scaled up to multi-ton capacity and the feasibility of decoupling positional adjustment from the survey process. Two separate prototypes- a Tri-Sphere Mechanism and a Portable Actuation Unit- were built and tested in support of these goals. The design parameters of the Tri-Sphere prototype were chosen to be consistent with some of the most demanding applications likely to occur in the ILC: a payload capacity of 10,000 kg, ranges of motion in the horizontal and vertical planes of ± 20mm (50 μm precision) and a resolution of 10 μm. The PAU was designed to accept and store displacement offset data, read standard barcodes, send step commands to stepper motors and measure resulting displacements in the horizontal and vertical planes.

Design of the Tri-Sphere Mechanism: A worm gear screw jack was chosen to provide vertical actuation. These jacks can be driven by either a ball screw or a machine screw. Although use of a ball screw requires less torque to operate, machine screw jacks with high gear ratios are self-locking and less expensive. For this application, a heavy-duty machine screw jack was ordered from Nook Industries: the 10-MSJ-UK with a gear ratio of 24:1 and a 2-in (50.8 mm) diameter screw with a ¼-in (6.35 mm) lead (Figure 1). This model is rated for a 10-ton (9,090 kg) load and ordered with 3 in (76.2 mm) of travel.

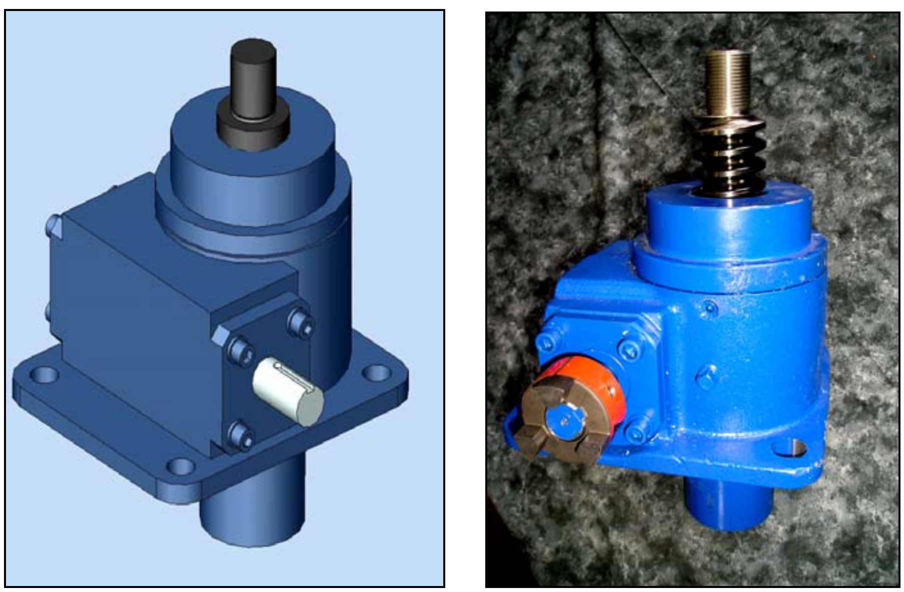


Figure 1: Primary Lifting Jack

A spline nut/shaft linkage was developed to drive the shaft of the screw jack. It allows torque to be transmitted from the PAU's motor to the screw jack while accommodating the horizontal movement of the carriage that supports the jack (Figure 2). The ball spline and ball nut were ordered as a unit from THK. The LBF 15 has a basic static torque rating of 659 lb·in (74.5 N·m) and a basic static radial load rating of 1,890 lb (8.4 kN). The custom components were machined from aluminum for this prototype.

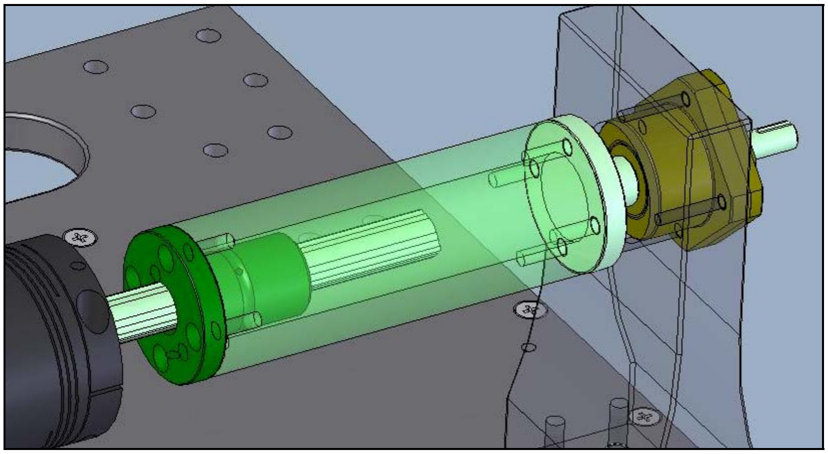
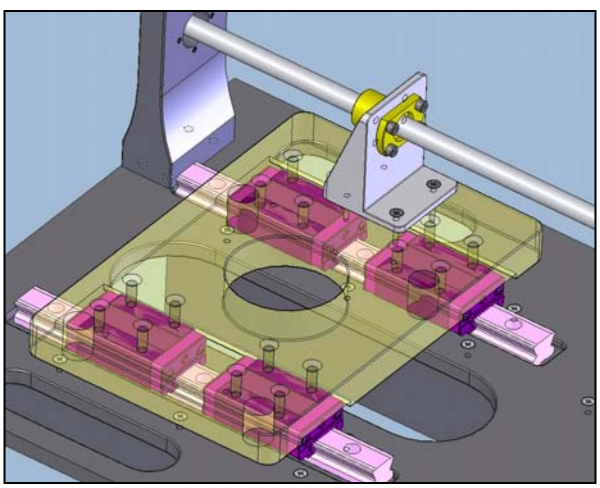


Figure 2: Spline Nut/Shaft Connection

Horizontal movement is provided by a carriage that rides on a set of rails and is driven by a ball screw assembly (Figure 3). All necessary linear motion hardware was provided by THK. The two rails, each 11.4 in (290 mm) in length, were supplied with two LM blocks and were machined to a standard accuracy. This hardware provides a high-rigidity horizontal guideway that has a compact, low-profile design. Each block is 3.27 in x 1.89 in (83 mm x 48 mm) and the two are mounted on the rails such that there is 1.10 in (28 mm) of space between their end pieces. Consequently, there is 3.78 in (96 mm) of horizontal travel available.



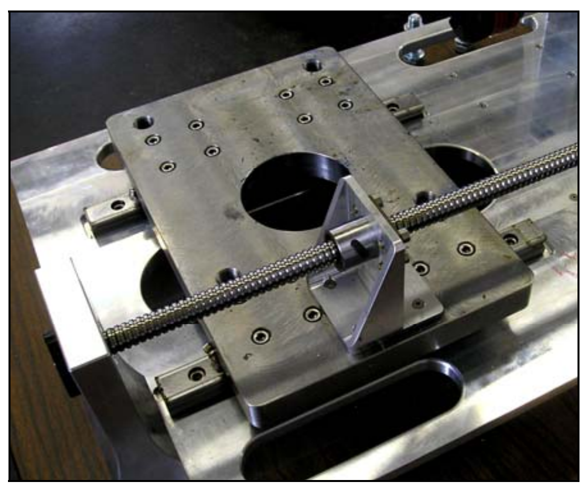


Figure 3: Horizontal Support Mechanism

The ball screw assembly, also obtained from THK, is the MDK 1404-3 with fixed end support units. The MDK 1404-3 has a screw shaft outer diameter of 0.551 in (14 mm) with a 0.157 in (4 mm) lead. The basic static load rating is 1,710 lb (7.6 kN). The support units were sized to integrate cleanly with the Mechanism's other hardware.

An 11.8 in x 7.87 in (300 mm x 200 mm) steel plate serves as the horizontal carriage and is attach to the LM blocks of the LM Guide SR via 16 M6 cap screws. The 10-MSJ-UK is in turn bolted to this steel plate. Finally, a mounting bracket for the ball nut of the MDK 1404-3 is attached to the plate with 4 M4 flat head screws.

Note: it would be possible to design a version of the Tri-Sphere Mechanism that does not make such extensive use of expensive linear motion hardware. For example, rather than riding on guide rails and bushings, a Mechanism's carriage could be designed to simply ride in dovetailed grooves machined directly into the base of the assembly. Similarly, the actuation of the carriage could be provided by a standard machine screw and nut. While these design simplifications would significantly reduce the cost of a Mechanism, they would also compromise its accuracy, precision and resolution. The design team chose to pursue the more sophisticated design as a means of establishing the system's upper levels of performance.

Custom parts were machined from aluminum and bolted together to form the Mechanism's frame. Short support legs were added to this frame to accommodate the extrusion that extends from the bottom of the worm gear screw jack. The rails of the LM Guide are attached directly to the platform of the frame with M6 cap screws. Other custom fixtures included mounts for the support units associated with the ball screw and spline shaft. The most critical element of the frame is its front face; this face provides the kinematic surface that interfaces with the PAU. An aluminum rod with a v-groove machined into one end is mounted horizontally across the face. The rod rests above the ball spline and ball screw mounts and is positioned such that the front plate of the PAU is accurately aligned with the actuation quills of the spline shaft and ball screw (Figure 4). Hooks on the PAU's front plate engage the rod and support the PAU.

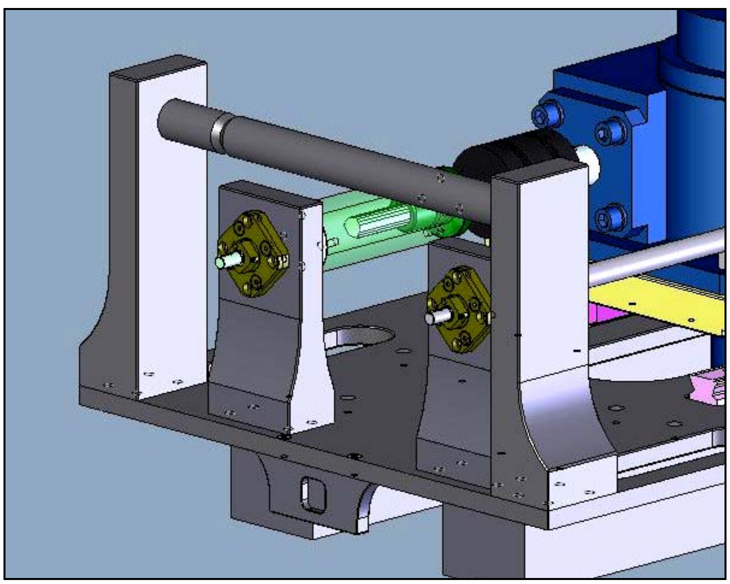


Figure 4: PAU Interface

Design and Testing of the Portable Actuation Unit: The design of the Phase I Portable Actuation Unit was initiated with the selection of appropriate commercial components. These components include a bar code reader for identifying a particular Mechanism, a compact flash card reader that holds the displacement offsets, a motor control card that converts displacement offsets to steps, a displacement gage and a PC-104 processor that supervises the unit's operations. The function of each of these components was independently verified and then they were combined into an "intermediate" prototype that validated Square One's integration strategy.

If time and budget allowed, the team planned to convert this intermediate prototype into a fully functional unit sized to drive the Phase I prototype Mechanism (Figure 5).

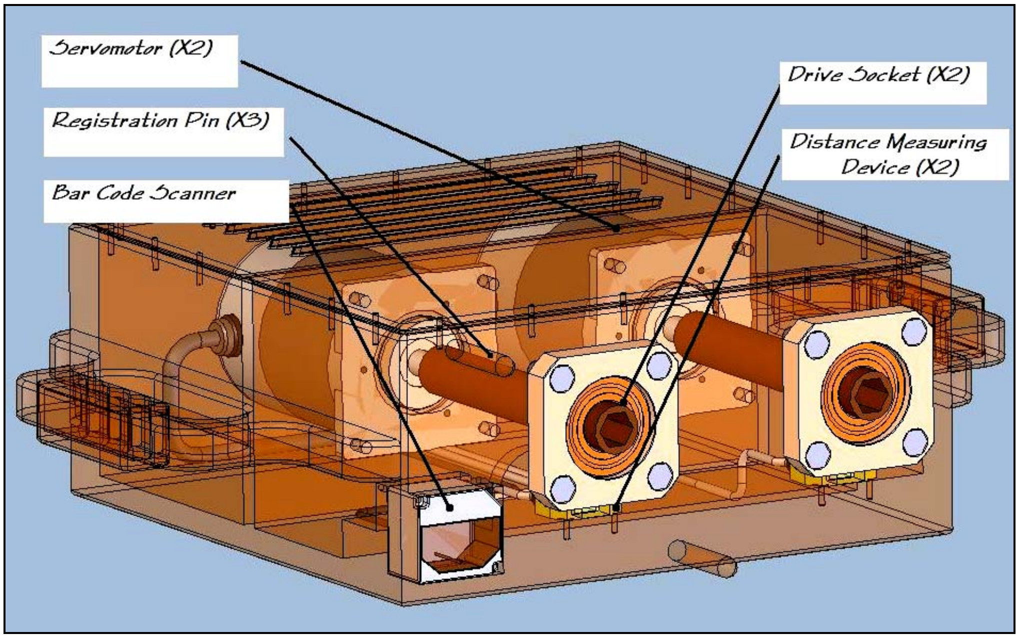


Figure 5: PAU Design

The Phase I Scope of Work envisioned using two, non-contact laser gages to measure horizontal and vertical displacements. Because of the expense of these gages, the design team decided to evaluate other options, including the use of relatively inexpensive contact gages. A series of benchtop tests were conducted during which LVDTs, cable pull gages and other devices were evaluated. Ultimately, the design team developed an innovative method of reflecting a measurement beam through 90°, allowing a single laser gage to read both horizontal and vertical offsets (Figure 6). Consequently, a Keyence LK-G series CCD displacement gage was selected for this application.

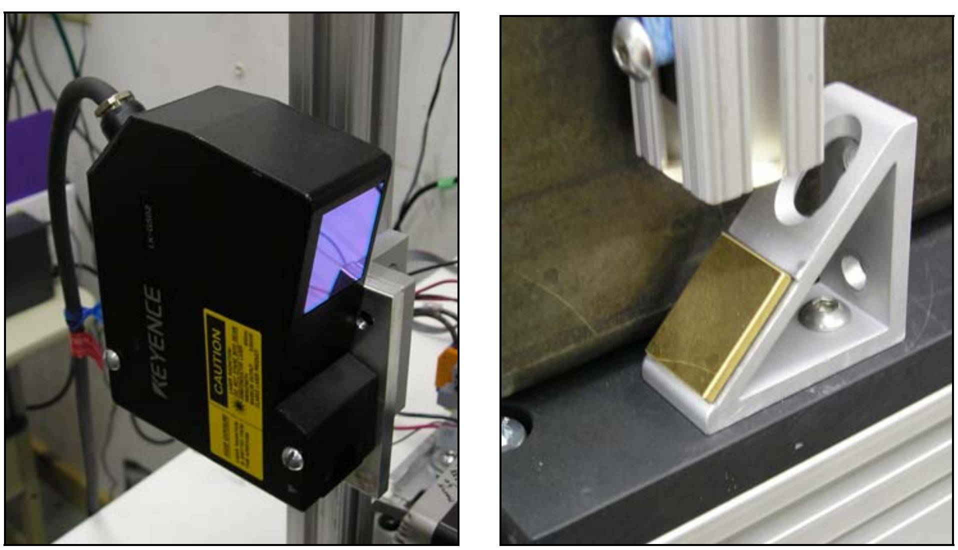


Figure 6: Laser Displacement Monitor

After the function of the PAU's individual components was validated, they were linked together and assembled into the intermediate prototype. The components were packaged in a box with simple buttons and lights acting as the operator interface. Two small stepper motors were mounted on an X-Y stage; this stage acted as the stand-in for a Tri-Sphere Mechanism. As the first step in testing the PAU prototype, the user created a file on a flash card containing a list of Mechanism ID's and associated offsets. This flash card was inserted into the prototype. Next, a bar code label was created and placed into a holder incorporated into the test station. The prototype was then signaled to begin a faux adjustment process. The bar code label was read and the associated offset date retrieved from the file loaded onto the flash card. These offsets were then converted into the appropriate step counts and the motors actuated. The resulting displacements were measured using the Keyence laser gage.

These tests demonstrated the prototype's ability to reliably read bar codes, even in low light or when a label was slightly damaged. They also demonstrated the prototype's ability to retrieve offsets from the flash card and accurately convert them into motor steps. Finally, they demonstrated the unit's ability to automatically measure the resulting displacements with a very high degree of precision. Tests were also performed that checked the unit's response to error conditions. These conditions included blank bar code labels, bar code labels with no corresponding offsets, missing laser targets and occluded laser lines of sight. All of these error conditions were detected and properly resolved.

With the success of the intermediate prototype, the Square One team moved to create a full-scale prototype PAU. As described above, the front of the Mechanism includes kinematic registration features. The PAU's faceplate is designed to interface cleanly with these features via two hooks and a tooling ball (Figure 7) allowing the PAU to be hooked into place and then lowered over the actuation quills. A faceplate was fabricated and tested and the utility of this method of linking the PAU to the Mechanism was validated. Next, MDrive motors were fitted to the PAU's faceplate and used to drive the prototype Mechanism. Because of time constraints, full integration of the final PAU did not proceed beyond this point. However, the design team is confident that the functionality of the PAU concept has been established.

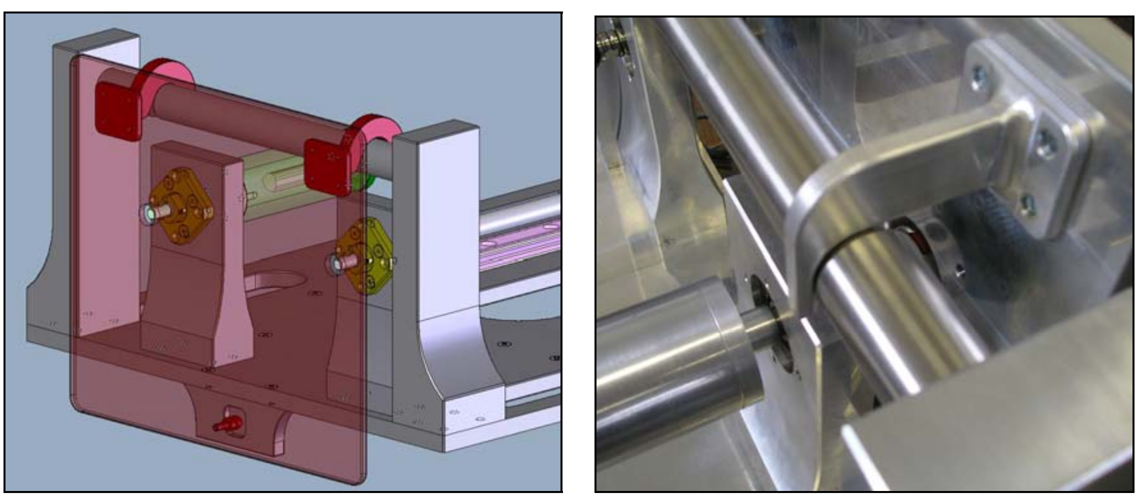


Figure 7: PAU Engagement Mechanism

Prototype Testing: The Phase I effort concluded with a test program to designed to quantify the performance of the combined prototypes.

The PAU faceplate was fitted with a pair of MDrive stepper motors and fitted into place on the prototype Mechanism. The Mechanism's kinematic features accurately registered the PAU's motors relative to the Mechanism's two actuation quills (Figure 8). The team determined that this method of mating the PAU to the Mechanism to be secure and very robust; it will require only limited modification as the project enters Phase II.

Figure 8: Operational Testing

Next, the motors were used to drive the horizontal and vertical axes of the Mechanism through their full ranges of motion. Motion was observed to be exceptionally smooth and free of any noticeable stick/slip. Ranges of travel were verified to match design specifications: ±46 mm along the horizontal axis and ±32 mm along the vertical axis.

The next phase of the test program attempted to quantify the accuracy and precision of each axis. Here accuracy is defined as the difference between actual component motion and the input command. Precision is defined as the range of deviations in output positions that result for the same input command. Actual displacements were measured using a Mitutoyo dial gage (Figure 9). This sensor has a measuring range of 2 mm and a resolution of 1 μm.

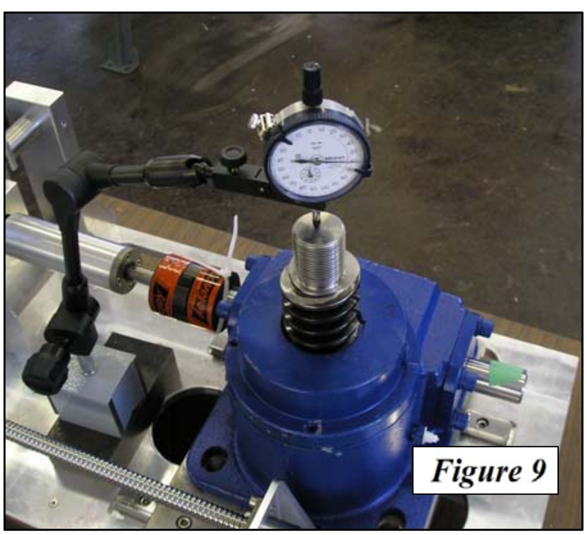


Figure 9

A 1.300 mm displacement command was given to the vertical mechanism and the resulting motion of the top of the screw was measured. This process was repeated 100 times and the resulting data were plotted. The accuracy is the difference between the peak of the normalized measurement distribution and the target value of 1.300 mm. The precision is the range of measured values that fall within two standard deviations of all the measurements. Accuracy was measured to be 20 μm and precision +/- 12 μm. Similar results were obtained for the horizontal axis. The design team later determined that poor tolerancing of the bushings fitted into the Mechanism's front plate added random errors to these measurements and prevented the Mechanism from achieving its full potential. It should be noted that since the actual displacement of an ILC lattice element within the tunnel will be measured independently using the PAU's laser gage, the inherent accuracy and precision of the Tri-Sphere system are not as critical as they would be in a conventional "open-loop" positioning system. However, the smaller these values are, the faster a closed-loop system will converge on a targeted displacement value.

Conclusions: While there remains room for improvement, the Square One team is very satisfied with the overall performance of the two prototypes. Once refined, the combined PAU/Tri-Sphere System will offer major advantages over all current support and adjustment mechanisms. We believe that our Phase I goal of demonstrating the feasibility of a high payload Tri-Sphere system has been conclusively achieved and that the path toward a family of production systems that meet the needs of the International Linear Collider is now open.