An Automated Magnet Positioning System
For Use in the Next Linear Collider

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1. Significance, Background Information and Technical Approach

1.1 Identification and Significance of the Opportunity and Technical Approach

The U.S. High Energy Physics community has recognized that research above the 1 TeV energy level is essential for a fuller understanding of the Standard Model. The front-running technology for achieving this ambitious energy goal is the International Linear Collider (ILC). As conceived, the ILC will bring a high energy beam of electrons into collision with an opposing high energy beam of positrons. It is designed to begin operation at 500 GeV center-of-mass collision energies and will be up-gradable to energies of 1 TeV and beyond.

Collision energy is one key element of a successful accelerator; the other is luminosity. The luminosity goal for Stage I (500 GeV cms) of the ILC is $2.0X10^{34}cm^{-2}s^{-1}$[12]. In order to achieve this luminosity, the beams will have to be very tightly focused as they are brought into collision. The current design parameters for the horizontal dimensions of the beams at their Interaction Points are 245 nanometers in the horizontal plane and only 2.7 nanometers in the vertical plane. Delivering beams with these tremendously compressed dimensions is one of the ILC's greatest technical challenges.

The design of the ILC is predicated on experience gained at earlier accelerators, particularly the Stanford Linear Collider (SLC). One of the innovative strategies that has allowed the SLC to achieve its ultimate luminosity is beam-based alignment: the location and shape of the beam are measured in transit by a series of high resolution beam position monitors. This beam "quality" information is then used to tune the positions of lattice elements within the accelerator in order to maximize luminosity. The ILC plans to make broad use of beam-based alignment in the Damping Rings and the Beam Delivery Systems [18]. In order to implement this strategy in the ILC, high-precision positioning systems, capable of being remotely operated, will be required to support key lattice elements throughout the collider. These remote positioners have been identified by the ILC design collaboration as a critical enabling technology.

A wide variety of mechanisms have been developed for adjusting the position of accelerator components. These mechanisms, usually assembled from an assortment of struts, machine jacks and stages, have often proved to be less than ideal. The perfect adjustment mechanism should provide solid support without over constraining the object being supported. It should have a wide range of travel in all six degrees of freedom with the fine resolution necessary to optimize the position of critical lattice elements. Finally, in order for it to be compatible with beam-based alignment, the mechanism must be able to be operated remotely.

Square One Systems Design believes that a novel type of precision manipulator, evolved from the family of positioning devices known as Stewart Mechanisms, could be adapted for use throughout the ILC. As envisioned, this "Tri-Sphere" Adjustment System will possess six, non-redundant degrees of freedom, be capable

of sub-micron resolutions and have an ultimate load capacity in excess of 10,000 kg. The system will accommodate thermal expansions and contractions of the objects being supported and can be either motorized or manually actuated. Square One proposes an applied research program to first establish this concept's feasibility and then to develop and test a family of Tri-Sphere positioning systems tailored to the needs of the ILC's array of lattice elements.

1.2 Anticipated Public Benefits

The primary goal the Tri-Sphere development effort is to contribute to the success of the International Linear Collider. This accelerator, as well as America's network of other particle accelerators, are vital national resources: "Accelerators underpin virtually every activity of the DOE's Office of Science and, increasingly, of the entire scientific enterprise. From biology to medicine, from materials to metallurgy, from elementary particles to the cosmos, accelerators provide our widow to the microcosm, forming the basis for scientific understanding and applications spanning countless fields." [5]

A versatile, high-payload positioning system such as the Tri-Sphere would be of immediate benefit to a variety of scientific activities. The Spallation Neutron Source, currently under construction at Oak Ridge, Tennessee, will eventually have over 14 independent beam lines delivering pulsed neutrons to an array of experiments. Each of these experiments will require specialized beam conditioning elements such as collimators, choppers and reflectors that must be very accurately positioned relative to the incident neutron beam. The Tri-Sphere System could be adapted for these applications as well as for the support and positioning of the very large detector elements associated with these experiments. The National Ignition Facility in Livermore, California has similar remote positioning requirements for its ultra-high energy laser delivery optics. Other particle accelerators currently in operation could benefit from the Tri-Sphere System as beam-based alignment strategies are applied to existing beam lines in order to improve their performance.

In the private sector the Tri-Sphere System would be a candidate for any application requiring high-precision position control in six degrees of freedom. An example at one end of the size spectrum would be the sub-micron manipulation of semiconductor photomasks during the electron beam pattern generation process. An example at the other end of this spectrum would be the active fixturing of multi-ton jet engines and other components during aircraft manufacturing.

1.3 Tri-Sphere Concept

Magnet supports, mechanical adjusters and alignment fiducials have always been critical elements of accelerator design. The quality and utility of these alignment elements have a significant impact on both an accelerator's performance and its cost [16]. As stated above, a variety of positioning mechanisms have been developed for accelerator applications. Historically, one of the most widely used mechanisms

has been the strut array. These arrays, belonging to a class of manipulators known as Stewart Mechanisms [8], are versatile and inexpensive. When properly arranged, they have the advantage of being kinematic: they allow the position of the object being supported (usually a magnet) to be adjusted in all six degrees of freedom without the possibility of over constraining the object. Unlike positioning mechanisms assembled from linear stages, strut arrays are not orthogonal: pure translations require that the lengths of *all* of the struts be adjusted. However, if absolute alignment tolerances are relatively loose, this actuator coupling, manifested as small cosine errors, is not generally significant. Strut Arrays do have some fundamental disadvantages: installation of magnets can be cumbersome, they cannot accommodate changes in a magnet's length due to thermal expansion during operation, they often have a limited range of motion and they are incompatible with motorized actuation.

In the early 1980's engineers at CERN produced variations on the strut array that attempted to address some of its inherent deficiencies. They demonstrated that three identical sub-mechanisms could be arranged to create a kinematic magnet mount. During this same period, Gordon Bowden and his colleagues at SLAC began their seminal development work on cam-driven magnet movers [2]. Both of these approaches have been successfully used in accelerator applications. The Tri-Sphere concept incorporates the best elements of these earlier devices along with several design innovations to create an adjustment system uniquely suited to the demands of the ILC.

The system's positioning strategy is illustrated in Figure 1. Three identical "jacks" provide support. Each of these jacks is adjustable in the vertical and *one* lateral direction but is unconstrained in the *other* lateral direction. The three jacks, each rotated 90° relative to its neighbor, are arranged in a triangle. The result is a large-scale, six degree of freedom adjustment system analogous to an optical gimble mount.
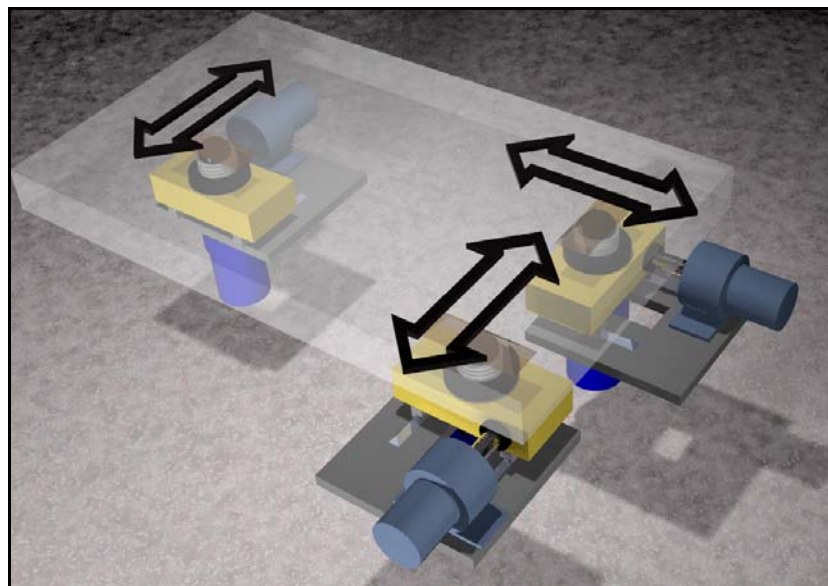

Figure 1

The basic Tri-Sphere mechanism is the practical realization of the jack described above. It is created using commercial motion control hardware arranged in a novel configuration. This basic mechanism is illustrated in Figure 2. A Traveling Block, riding on a pair of linear bushings, is driven in the horizontal plane by a motorized lead screw. A Central Ball Screw, driven by a geared motor connected via a spline shaft, provides vertical adjustment. This Central Ball Screw is topped by a steel Contact Sphere that acts as the interface between the mechanism and the object being supported. Three of these spheres engage V-shaped grooves incorporated into the bottom of the object. These grooves are oriented at right angles to the lead screws that drive the Traveling Blocks. Because of the design's inherent compliance, an object does not have to be precisely located relative to the three support points when being installed; it simply needs to be lowered into a nominally correct location and it will be "snapped" into place by gravity.
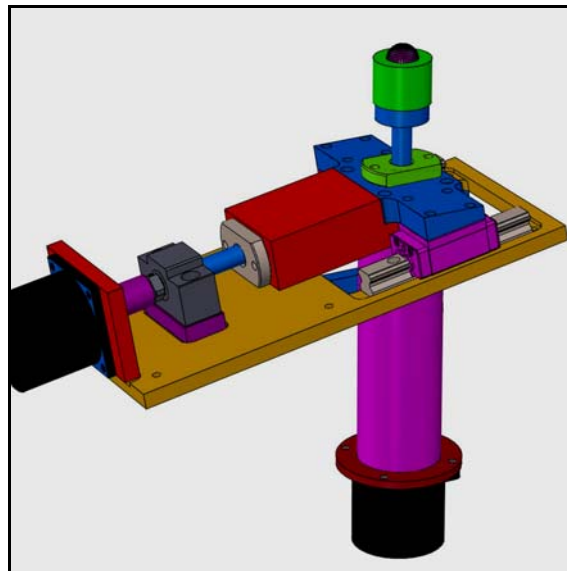

Figure 2

In order for the system to be used with beam-based alignment, an algorithm must be developed that relates the coordinate system of the Tri-Sphere Adjustment System to the coordinate system of the beam. More specifically, this algorithm must allow the computation of rotational offsets for each of the system's six actuators that will result in the movement of a lattice element from its current location to a new "target" location. This algorithm takes the form of the inverse kinematic equations for the Tri-Sphere manipulator [10].

One anticipated benefit of the Tri-Sphere system is the potential to rapidly pre-align magnets and accelerator supports. Under this plan, a Tri-Sphere System's Contact Spheres are replaced with appropriate alignment targets prior to component installation. These targets could potentially be Taylor-Hobson balls, socketed

corner cubes or conventional laser targets. Next, the space coordinates of these targets are measured by the survey team. These measurements can then be used to compute the *anticipated* location of the associated lattice element in *any* arbitrary coordinate system. Actuator offsets are then computed and communicated to the TriSphere Systems allowing components to be placed very near their optimal locations during installation. A more complete discussion of this alignment strategy is included in Section 2.2, Task 11.

1.4 Degree to which Phase I has Demonstrated Technical Feasibility

Phase I Prototype Design: The basic design parameters of the Phase I prototype had to be chosen such that the resulting system would be capable of providing conclusive insight into the Tri-Sphere concept's feasibility. Thus, it was essential that this prototype be sized to support significant loads, that its range and resolution were consistent with the anticipated needs of the ILC and that it could be remotely operated via a straightforward user interface. The limits of our development effort were defined by the budget and schedule constraints of the Phase I SBIR grant. Working within these constraints, the Square One design team identified the following performance targets for the prototype:

System Parameter	*Target Value*
System Footprint	Less than 1 meter by 1 meter
Degrees of Freedom	Six
Payload Capacity	Greater than 100 kg
Translational Range of Motion	Greater than 20 mm
Accuracy (Mechanism Axis)	5 microns
Precision (Mechanism Axis)	+/- 5 microns
Resolution (Mechanism Axis)	Less than 1 micron
Operational Mode	Fully Automated
Operator Interface	Graphical Touch screen

Square One's earliest conceptual designs for the manipulator were informally reviewed by alignment specialists at both SLAC and Fermilab. These reviews resulted in a series of recommendations that led to significant modifications of this original concept. The first modification was to revise our design so that all sliding contacts were eliminated from the baseline mechanism. SLAC's Gordon Bowden pointed out that no matter what type of lubrication is employed, friction between sliding surfaces will prevent reliable system performance in the realm below 1 micron. The next modification was to add a pre-load to the horizontal axes of the baseline mechanism with the goal of minimizing the manipulator's backlash. Return springs were considered and rejected. The preferred solution was the addition of a 10° spacer below the formerly horizontal axis of the baseline

mechanism. The design team reasoned that since the Tri-Sphere layout was already non-orthogonal, the addition of this gravitational pre-load simply added a few additional terms to the system's kinematic equations.

If the Tri-Sphere Adjustment System is to find wide application in the ILC, it is essential that it be relatively inexpensive to produce. To help realize this objective, Square One designed the Phase I prototype to take full advantage of standard, off-the-shelf componentry. The design team chose THK as the source for all necessary linear motion hardware. This decision was based on THK's wide range of precision componentry, reputation for quality and rapid delivery. The ball screw/nut combination used to drive all six axes had the biggest impact on system performance. The MTF 1202-3.7 ball screw has a diameter of 12mm and a pitch of 2mm per revolution; we chose this fine pitch in an effort to maximize the prototype's resolution. The spine nut/shaft combination (LT13) that ties the vertical ball screw to the motor was chosen to match the ball screw diameter. The Traveling Blocks were mounted on standard HSR 15 square bushings riding on a pair of low-profile rails. We originally planned to use four of these bushings to support the Traveling Block but analysis indicated that two would be sufficient. The resulting design for the Phase I prototype is illustrated in Figure 3.
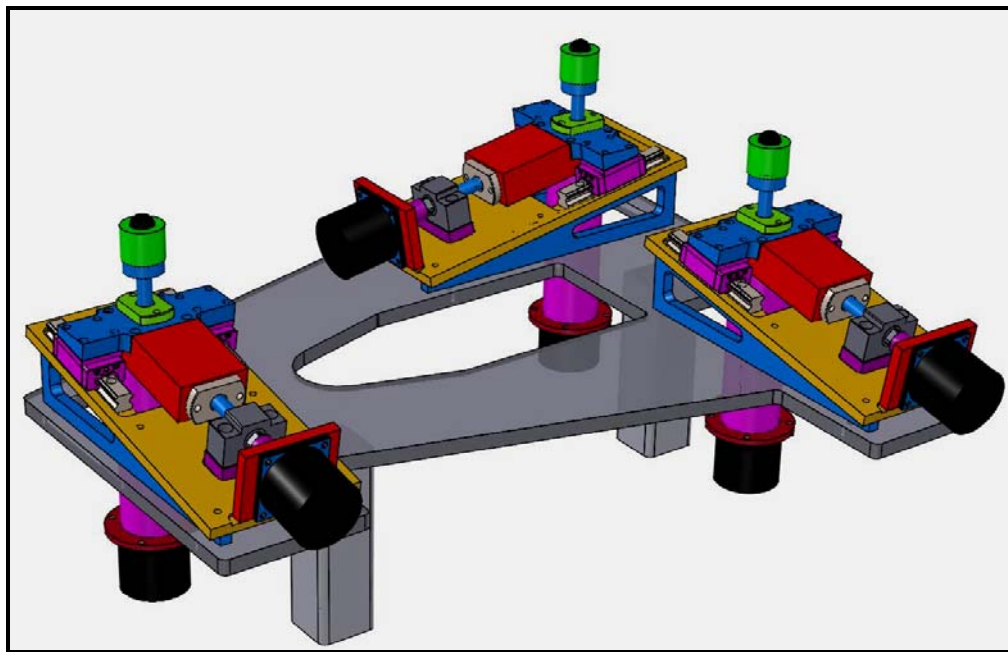

Figure 3

Several motor options were explored to drive the prototype. These options included stepper motors, servomotors and hybrid motors. Ultimately, the decision was made to equip the prototype with QuickSilver I-Grade Motors. These high pole-count servomotors perform well at low speeds and their internal encoders deliver 8,000 counts per revolution. Each motor is mated with a QuickSliver "Silver Nugget"

controller. These controllers are configured using Quick Control, a Windows-based software package that provides for basic motor functions such as self-centering and "soft stops" at each axis's limits of travel. The motors' 8,000 counts per revolution coupled with the 2mm ball screw pitch results in a theoretical mechanism resolution of 250 nanometers. The ability to set soft stops allows the system to be safely operated without the need for additional end-of-travel sensors. Because of the system's very low inherent friction, a decision was made to integrate brakes into all six of the prototype's axes. The team felt that it was important to demonstrate the system's positional stability under all conditions, including a loss of power.

While it would have been possible to have controlled the prototype via the Quick Control software, the operation would have been slow and cumbersome. More importantly, reviewers at the National Labs repeatedly stressed the importance of equipping any automated positioning system with an intuitive, easy-to-use operator interface. Consequently, a Red Lion G3 touch screen interface was incorporated into the controls architecture. In addition to providing touch screen commands to activate the motors, the G3 performs the calculations needed to convert desired translational or rotational object moves into the number of counts that each individual motor must move. Programs were written and screens created for the G3 using Red Lion's Windows-based Crimson 2.0 software. Examples of these operations screens are shown in Figure 4. Utility screens allow an operator to set system parameters such as step size, velocity and acceleration and higher-level screens provide for normal operation of the system. The G3 also provides a remote Web access and control capability via its Ethernet port.
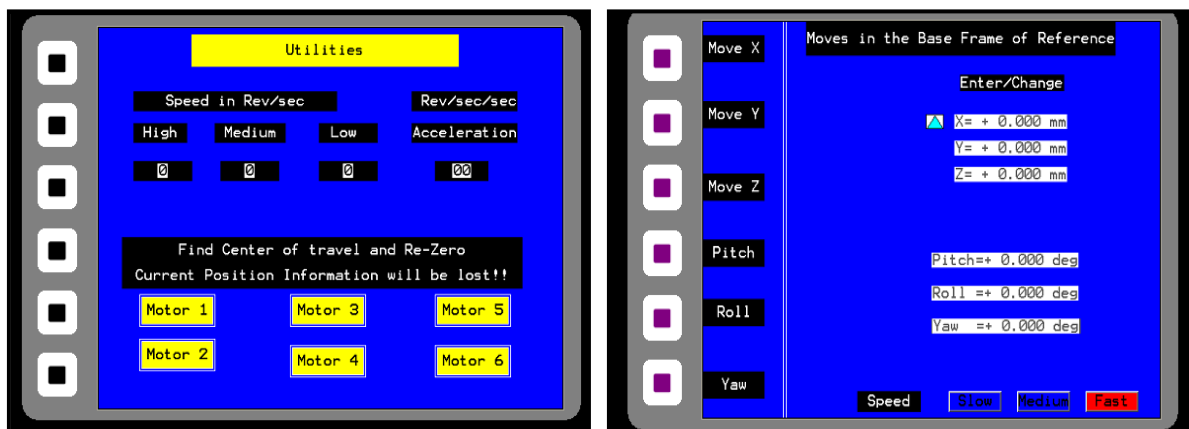

Figure 4

Once the prototype's design was finalized and its commercial components chosen, orders were placed for the necessary fabricated parts. Because all relative movements between these parts would be borne by linear motion hardware, it was not necessary to plate or otherwise specially finish the parts. Exceptions were the cups that hold the Contact Spheres: these were nickel plated for hardness and durability. Final assembly and initial power-up of the prototype was performed at

Square One's Jackson, Wyoming facility. The finished prototype is shown in Figure 5.
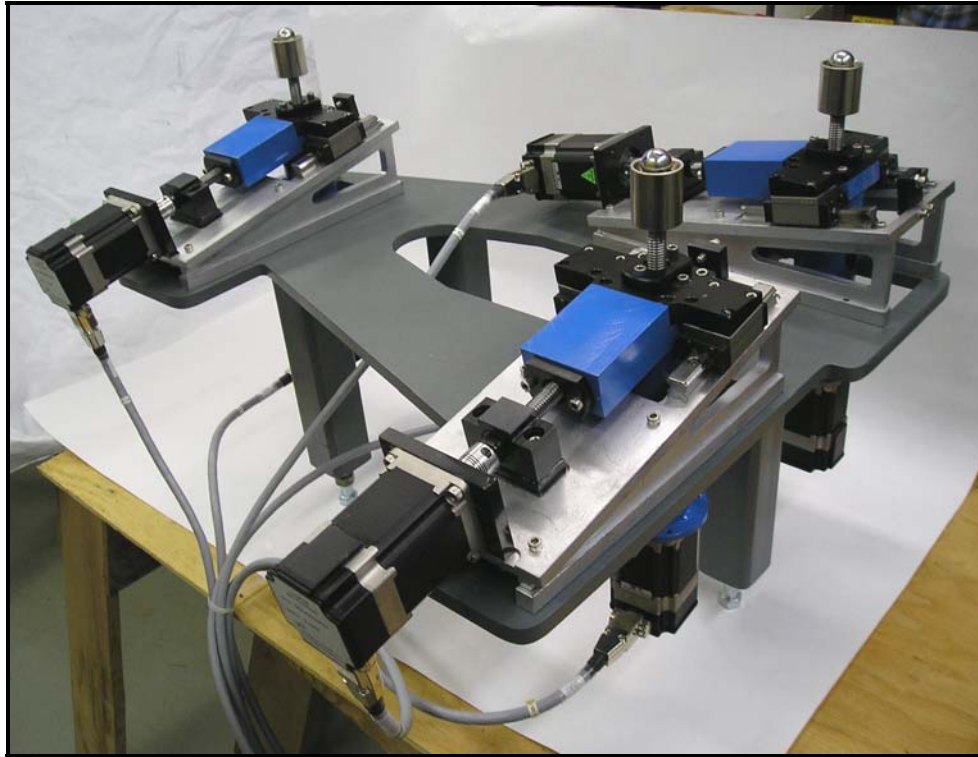

Figure 5

A test load was also fabricated. This load is a simple steel plate fitted with stainless steel "V"-groove blocks. The location of these blocks matches the geometry of the manipulator.

Test Program: The first functional test performed was a qualitative measurement of the prototype's basic support stability. The three mechanisms were placed at their centers of travel and the test load was set in place. As was expected, the plate "snapped" into a secure, stable and unique location atop the Contact Spheres (Figure 6). One problem noticed earlier in the project manifested itself: during assembly, the THK ball screw/nuts exhibited a small but noticeable amount of lateral play. When a lateral force was applied to the test load, a small displacement, roughly equal to the play in the ball screws, could be observed. The proposed solution to the problem is described in Section 2.2. A second qualitative experiment

Figure 6

measured the ability of the test load to repeatably return to the same location each time it was removed and then replaced onto the Contact Spheres. Tests verified that this was, in fact, the case.

The first quantitative experiments measured the prototype's translational range of motion. The design range for each mechanism axis was 25mm but this range was slightly truncated by the system's soft stops. The actual translational ranges of motion in X, Y, Z were measured to be between 22.1mm and 22.7mm. The choice of a 25mm range for the prototype was somewhat arbitrary; there is no inherent reason that a Tri-Sphere system with a much larger range of motion could not be constructed. Rotational ranges of motion were not measured directly but, based on the measured translational values, were computed to be 80.7 mrad in Pitch, 162.0 mrad in Roll and 45.6 mrad in Yaw.

The prototype's payload capacity was measured by progressively placing more weight on the top plate and performing 5mm vertical translations. The QuickSilver motors were sized to lift a *minimum* of 100 kg. Tests verified that the prototype was capable of lifting 105 kg. We were reluctant to test the system to "failure" for fear of damaging the motors but it is likely that the prototype is capable of lifting payloads far in excess of this measured value.

The next phase of the test program attempted to quantify the accuracy and precision of an individual mechanism's horizontal 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 Keyence LK-031 laser displacement sensor. This sensor has a measuring range of +/- 5mm and a resolution of 1 micron. A 1.000mm horizontal displacement command was given to the mechanism and the resulting motion of the traveling block was measured. This process was repeated 100 times and the resulting data were plotted (Figure 7). The accuracy is the difference between the peak of the normalized measurement distribution and the target value of 1.000mm. The precision is the range of measured values that fall within two standard deviations of all the measurements. Accuracy was measured to be 1.8 microns and precision +/- 4.5 microns. While these measurements have not yet been repeated for the prototype's other five axes, it is reasonable to assume that results will be similar. It should be
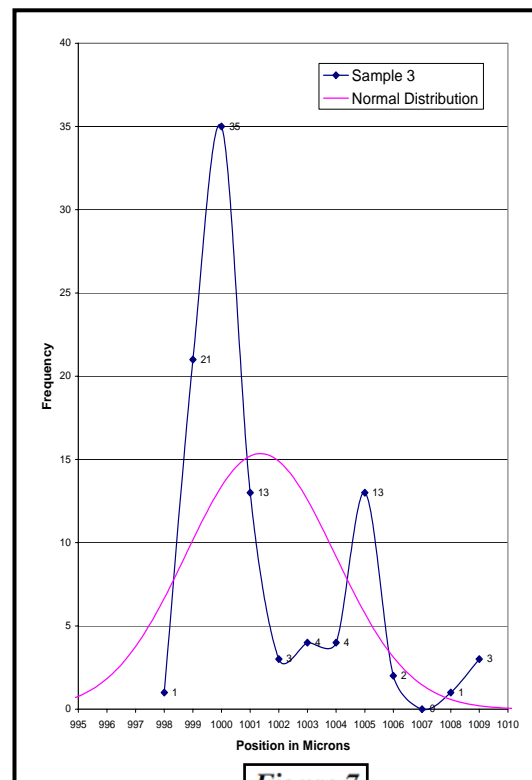

Figure 7

noted that since the actual displacement of an ILC lattice element within the tunnel will always be measured independently, 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 two values are, the faster a closed-loop system will converge on a targeted displacement value.

The final phase of the test program attempted to measure the prototype's resolution. Again, we restricted ourselves to an individual mechanism's horizontal axis. Unfortunately, the limitations of our measuring instrumentation made it impossible to directly measure the 250 nanometer translation that theoretically corresponds to a single count input. Instead, we were obliged to input a sequence of single counts while recording the laser sensor's micron-level readout. When plotted (Figure 8), these data do suggest that submicron resolution has been achieved. During the collection of these data the axis's direction of travel was reversed and then reversed again; the narrow hysteresis loop that resulted indicates that the axis under test has very minimal backlash.
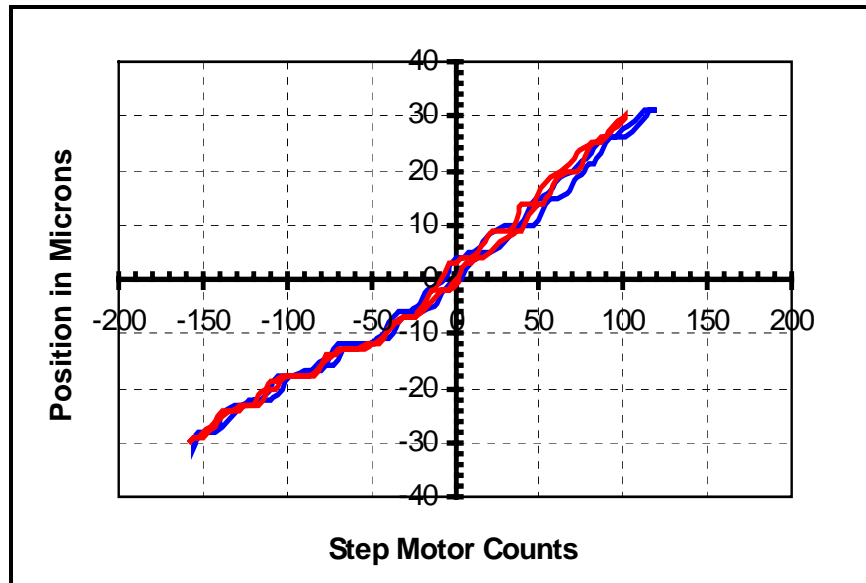

Figure 8

Conclusions: Based on the test program, all of the prototype's fundamental performance targets have been met. However, in the course of evaluating the prototype, several problems did manifest themselves. As described above, the play in the ball screw/nut combination led to minor instabilities of the test load. In addition, fabrication inaccuracies created slight misalignments between the primary axes of the vertical ball screws and the primary axes of the cups that hold the Contact Spheres. When the prototype's vertical axes were "spun-up", these misalignments resulted in small, off-axis errors. Design modifications that address the sources of these errors are described in Section 2.2. The QuickSilver motor controllers have encoder error thresholds designed to eliminate servo hunt. While these thresholds did succeed in forcing rapid command-encoder convergence, we

discovered that when set too high they also limited the resolution that the system could achieve. Revisions to these algorithms will be necessary in order for the Tri-Sphere system to reach its full potential. While there remains much room for improvement, the Square One team is very satisfied with the overall performance of the prototype. We believe that our Phase I goal of demonstrating the feasibility of the Tri-Sphere concept has been conclusively achieved and that the path toward the development a commercial system for use throughout the ILC is now open.

2. Suggestions for System Improvements

2.1 Redesign of the Tri-Sphere's Vertical Axis

As outlined in Section 1.4, the Phase I Tri-Sphere prototype exceeded its target performance parameters. However, minor problems were discovered during the system's test program. Chief among these problems were the small off-axis errors (the difference between ideal straight line motion and actual measured motion) associated with the basic mechanism's vertical axis. When vertically actuated, the Contact Spheres were observed to wobble slightly; this behavior was measured, to a greater or lesser degree, in all three mechanisms. This wobble produced small, random errors in X and Z that were superimposed upon the desired Y translation. The cause of this problem was determined to be fabrication inaccuracies that resulted in the primary axes of the Contact Sphere cups being slightly offset from the axes of the vertical ball screws.

A second problem was discovered with stability of the vertical ball screws themselves. The fine thread pitch (2mm per revolution) of these ball screws corresponded to a relatively narrow screw diameter (12mm). While this diameter was more than adequate to support the target payload, all three screws exhibited a small amount of "play" within their ball nuts. When these screws were incorporated into the prototype, this play resulted in small lateral instabilities of the test load. These instabilities became most pronounced when the three vertical axes were fully extended.

While both of these problems could be ameliorated through tighter tolerancing and improved component selection, a superior solution would be to redesign the vertical axis of the basic Tri-Sphere mechanism to include a pair of linear guides. These guides would ensure stable, on-axis vertical translation. Another advantage of this strategy is a greatly simplified vertical drive train: as illustrated in Figure 9, this modified drive train would not require a spline nut, spline shaft or telescoping coupling. This redesign will also result in a significantly more compact system.
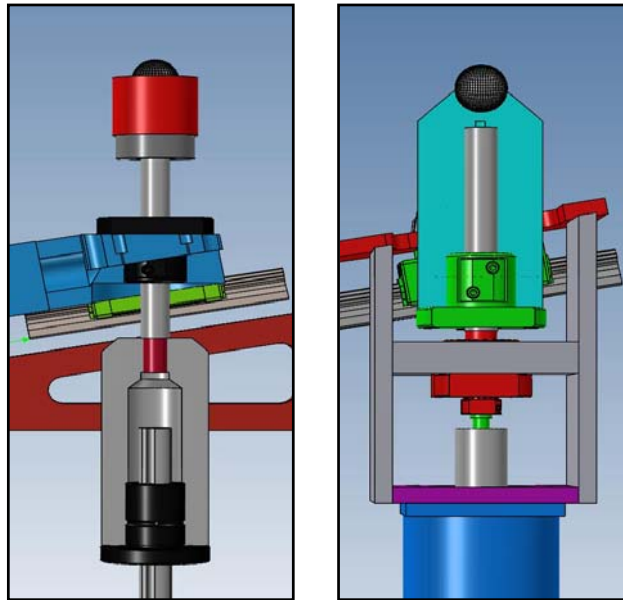
Figure 9

2.2 Improved Drive Components and Other Enhancements

The Square One design team was satisfied with the performance of the QuickSilver high pole-count servomotors and intends to retain these motors in the Tri-Sphere's baseline design. These motors delivered 8,000 counts per revolution resulting in positional resolutions of 250 nanometers. The addition of mechanical gear reducers might improve the system's positional resolution by at least one order of magnitude. Gear reducers would also allow the second generation prototype to be driven by smaller motors and for those motors to operate at higher speeds. Potential downsides to this addition of gear reduction would be increased mechanical complexity and increased backlash.

Long-term operational considerations such as material stability, thermal expansion and appropriate exterior finishes should also be investigated. Mechanical improvements could be made to the Traveling Block in an effort to simplify the horizontal drive train. The controls architecture could be refined to address minor performance issues identified during initial prototype testing. These issues include detection of each axis's limits of travel, the setting of "soft stops" based on these limits, encoder resolution and error recovery. Finally, the Red Lion operator interface could be revised to make it more user-friendly and additional diagnostic screens will be added to the display. Figure 10 illustrates a conceptual design for this "next generation" Tri-Sphere system.
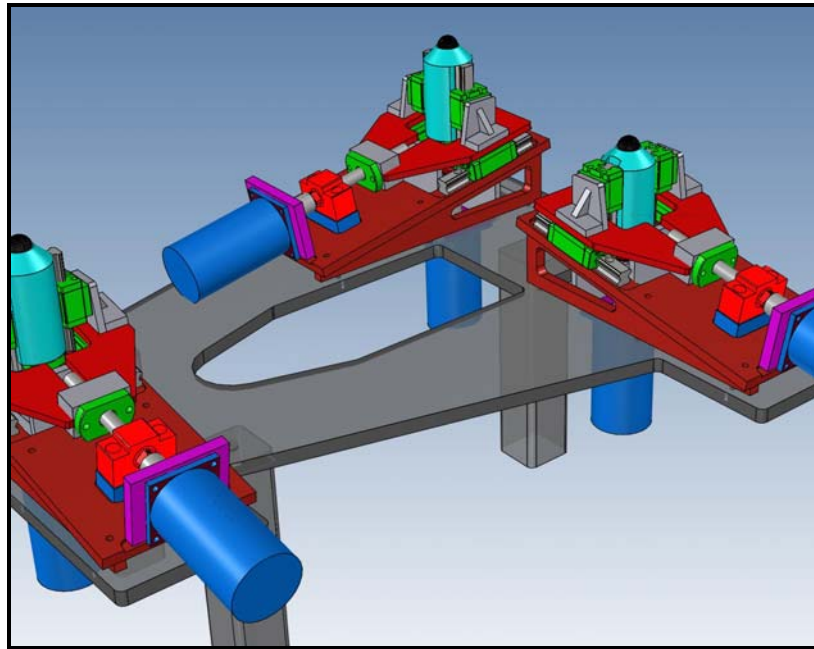
Figure 10

3. Potential Applications within the International Linear Collider

The decision to base the design of the ILC's Main Linacs on the superconducting L-Band technology developed by DESY has a major impact on the design of the adjustment system deployed in this region of the accelerator. On one hand, the support strategy is simplified: because of the L-Band modules' large iris radius, the Main Linac will be less susceptible to small misalignments and active positioning will probably not be required [18]. On the other hand, the length and weight of these massive superconducting cryomodules (Figure 11) will require exceptionally robust, high-capacity manipulators capable of providing both stable support and precision adjustment.
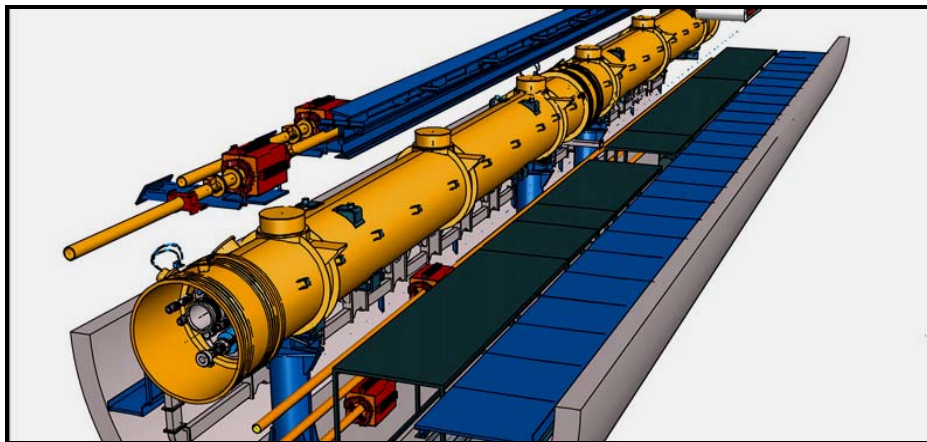

Figure 11

Current estimates are that more than 1,500 cryomodules will be required for the ILC's two Main Linacs. Consequently, it is essential that the design of the associated Tri-Sphere system not only meets the Linacs' positioning requirements, but also be consistent with economical mass production: design for manufacture will play a central role in this development effort.

Based on current knowledge of the TESLA cryomodule design [13], Square One envisions a rugged, manually-actuated version of the Tri-Sphere capable of supporting several thousand kilograms; the system's linear motion hardware would be scaled to meet this payload requirement. The in-line vertical drive train of the automated manipulators would be replaced with a right-angle worm gear. The addition of this reduction gear offers two significant benefits: it provides the mechanical advantage needed to more easily lift a multi-ton cryomodule and it places the vertical actuator *parallel* with the manipulator's horizontal actuator. A possible Tri-Sphere configuration for supporting the ILC's cyromodules is illustrated in Figure 12.
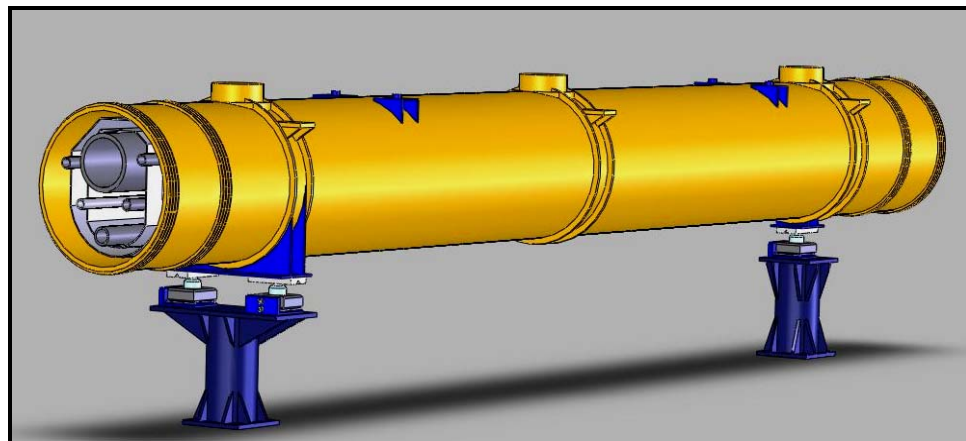

Figure 12

4. The Tri-Sphere System's Potential for Pre-Alignment

A fundamental property of the Tri-Sphere concept is that the locations of a manipulator's three Contact Spheres completely define the location of the object they support. Another important property of the Tri-Sphere is that, while highly coupled as a system, each individual mechanism is entirely *uncoupled* from the its neighboring mechanisms. Together, these properties suggest an innovative method for rapidly and efficiently pre-aligning an accelerator.

For the ILC's Main Linacs, the proposed process would work as follows. First, the support pedestals are installed in their nominal locations; the placement tolerances for this installation can be relatively loose, needing only to fall within the adjustment range of the Tri-Sphere systems used in the Main Linac. Next, the Tri-Sphere manipulators are installed atop the pedestals. At this point in the process,

the Contact Spheres have <u>not</u> been placed in the Tri-Spheres' cups. Once the manipulators are in place, a team begins the Main Linac survey. For the purposes of this discussion, we assume these surveyors are equipped with a state-of-the-art laser tracker such as the Leica LTD500 [17]. The team places spherically housed corner cubes matching the diameter of a Contact Sphere into a Tri-Sphere's cups (Figure 13) and measures their coordinates. These coordinates are entered into a master database. Because the spatial relation between each cryomodule's beam center and its V-groove "feet" will be known with great accuracy, the process described above is tantamount to performing a survey of a string of cryomodules *after* they have been installed in the tunnel.
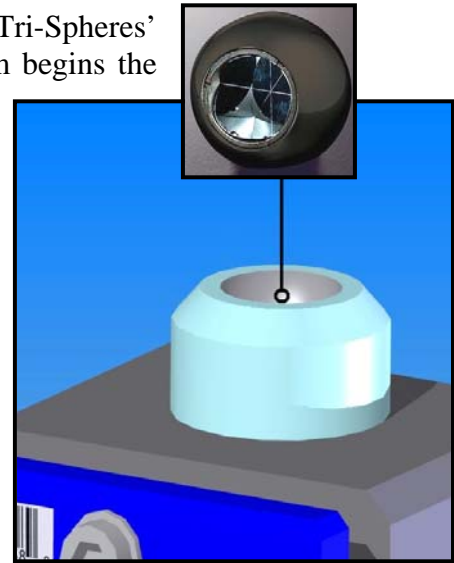
Once the database is filled, the "virtual" locations of the cryomodules are computed and conventional smoothing algorithms are applied. The resulting ideal locations for each cryomodule define new space coordinates for the Contact Spheres and thus horizontal and vertical offsets for each individual Tri-Sphere mechanism. Because the mechanisms are uncoupled, the adjustments necessary to place the virtual cryomodules in their target locations can be performed <u>without</u> the oversight of the laser tracker. An operator simply attaches a distance measuring device onto the Tri-Sphere mechanism, references it to an appropriate surface and generates the prescribed offset. Once a sector is aligned, the Contact Spheres are placed into their cups and the cryomodules are transported into the tunnel and "snapped" into place atop the Tri-Spheres. Square One anticipates that the resulting cryomodule-to-cryomodule alignment would be excellent.

5. References

1. Adept Technology Resource Group, "AdeptMotion VME Developer's Guide", 00961-00830 Rev. B, December 1996

2. G. Bowden, P. Holik, S.R. Wagner, G. Heimlinger, R. Settles, "Precision Magnet Movers for the Final Focus Test Beam", *Nuclear Instruments and Methods* 368A, 579-592, 1996

3. C. Buffo, E. Borissov, H. Carter "Linac Girder R&D", NLC Machine Advisory Committee, June 2003

4. J. Cornuelle, "Cost Estimation and Analysis: Mechanical Systems", NLC Machine Advisory Committee, June 2000

5. DOE Office of Science, "Strategic Plan 2004"

6. DOE Office of Science, "Facilities for the Future of Science; A Twenty-Year Outlook"

7. D. Edwards, M. Syphers, "An Introduction to the Physics of High Energy Accelerators", Wiley-Interscience, 1992

8. K. Hunt, "Kinematic Geometry of Mechanisms", Cambridge University Press, 1978

9. T. Kane, "Analytical Elements of Dynamics", Stanford University Press, 1978

10. Y. Nakamura and H. Hanafusa, "Inverse Kinematic Solutions with Singularity Robustness for Robot Manipulator Control", *ASME Journal of Dynamic Systems*, Vol. 108, 1986

11. NLC Design Collaboration, "Zeroth-Order Design Report for the Next Linear Collider" SLAC-474, 1995

12. NLC Design Collaboration, "2001 Report on the Next Linear Collider" SLAC-R-571, June, 2001

13. C. Pagani, et. al., "The TESLA Cryogenic Accelerator Modules" TESLA Report 2001-36, DESY, 2001

14. T. Raubenheimer, "JLC/NLC Accelerator Design and Luminosity Issues" NLC Machine Advisory Committee, November 2002

15. B. Roth, "Performance Evaluation of Manipulators form a Kinematic Viewpoint", National Bureau of Standards, 1975

16. SSC Central Design Group, "Conceptual Design of the Superconducting Super Collider", SSC-SR-2020, March 1986

17. D. Trbojevic, et. al. "Alignment and Survey of the Elements in RHIC", Brookhaven National Laboratory Internal Document, August, 1998

18. US Linear Collider Steering Group, "U.S. Linear Collider Technology Options Study" March 4, 2004

19. K. Waldron and J. Reidy, "A Study of Kinematically Redundant Manipulator Structure", *Proceedings of the IEEE Robotics and Automation Conference*, San Francisco, 1986