The performance of the NLC is affected by the positioning of its components. Position tolerances range from microns to nanometers for various elements. The allowable motion is a function of the temporal and spatial frequency of the motion. We look at sources, effects, and control of vibration in the NLC.

We divide the Vibration problem into the following:

**Beam effects and tolerances:** This is a beam physics issue of the allowable position errors for components. These errors are a function of the spatial frequencies involved. By definition they do not include any time dependence (beam feedbacks are included in the feedbacks section). This is a fairly easy to model, and well understood problem.

**Sources:** The fundamental sources of vibration are seismic and cultural. The seismic component is well understood, but probably not the most significant. The cultural sources are not well understood.

**Supports:** The NLC uses a large number of mechanical supports for devices. Both the static (drift/creep), and dynamic (resonant frequency, mechanical Q) properties of these supports are important. In addition some supports must include feedback actuators of some type.

**Feedbacks:** The NLC will use a variety of feedbacks to control vibrations or their effects. These feedbacks will use both electron beam and mechanical measurements, and will control both electron beam and mechanical actuators. The performance of these feedbacks depends on the frequency response of the actuators, and on the response of the mechanical supports for the devices. These interactions can be very complex.

**Final Focus System:** The final focus system has a variety of unique vibration issues.

**Beam effects and Tolerances:**

The tightest constraint on the positioning of beam components is the requirement that the nanometer scale beams collide at the IP. Any device motions which result in differential motion at the IP at the nanometer level must be controlled. The effects of component motion on the electron beam were studied in the ZDR. The tolerances are dependant on the correlation length of the disturbance. Roughly speaking, uncorrelated motions in the main linacs must be less than 5nm RMS, and the motions of the final doublet must be less than 1nm RMS.

Beam based feedback (discussed later in the feedback section) can attenuate motions with time constants longer than the interpulse period approximately by the ratio of the disturbance time constant to the interpulse period. For slow motions the tolerance is not determined by the beam colli-
sions, but by emittance degradation due to dispersion. The tolerance for slow motions is a few microns for the linac quads.

The ZDR design assumed electromagnetic quads in the Linac. Alignment was performed by shunting quads, and adjusting their position to null the beam steering. We are now planning on using permanent magnet quads for which there is no clear shunting mechanism. Note that if moving mechanical components are used for shunting, the magnetic center of the quad may move when the field is changed. There are a variety of possible alignment schemes:

- **Quad Shunting:** There may be a scheme for shunting the quad fields without moving the centers by more than the tolerance.

- **Dispersion free alignment:** The electron beam energy is varied, presumably as an energy bump which is moved down the length of the machine. The centers of the quads are deduced from the measured dispersions. It may be difficult / impossible to separate out the effects of RF steering due to mis-alignments of the structures.

- **Dead reckoning:** It may be possible to measure the alignment of the quads relative to the BPM center in the lab to the required accuracy. It may then be possible to have sufficient stability between the BPM measurement center and the quad center that the BPM readings can be used to determine the quad center.

- **Full alignment stability:** Ideally, the structures, BPMs and magnets would be assembled on a girder, aligned in the lab, and then maintain that alignment indefinitely. The entire girder would be aligned using the structure transverse mode BPMs. This would eliminate the need for many movers.

**Projects:**

Evaluate the use of dispersion free alignment. This is a study of the performance alignment algorithms with assumed BPM performance, wakefields, and calculated RF steering effects. Evaluate both invasive and non-invasive alignment techniques.

Evaluate the stability requirements (mechanical and electronic) for “dead reckoning” alignment. Consider use of strip line, cavity, and structure BPMs.

**Sources:**

Seismic sources have been well characterized at a variety of sites. Calculations based on the seismic noise at “quiet” sites indicate that the vibration levels do not cause significant luminosity degradation.

“Cultural” noise both due to the accelerator, and due to external sources (roads, industry, rivers, etc.) are less well characterized. Unfortunately it is these “cultural” sources which are likely to dominate in the frequency range of interest.
There are a variety of cultural sources of vibration which will not be under the control of the NLC designers. Data on the vibration spectrum as a function of distance from these sources needs to be collected and/or measured. In some cases the data may restrict the possible locations of the accelerator. In others, it may provide data on the vibration that is to be expected. Of particular interest are:

- Roads, Railways, Airports, Shipping, Aqueducts, Pipelines (including pumping stations), Various manufacturing and processing plants, Mines (blasting?), Conventional construction (excavation equipment, pneumatic hammers), etc. Some of the above sources may produce vibration over large areas. It may not be possible to exclude the future addition of these sources near the NLC.

NLC vibration sources must also be characterized. These include:

- Water pumps, fans, water flow in pipes, helium liquefiers, HVAC systems, etc. The transmission of vibration from these sources must be considered. Ground (and building) vibration transmission curves (as a function of frequency and distance) need to be collected and/or measured. These sources must either be shown to be insignificant, or a vibration spec for each must be developed.

Projects:

Evaluate the vibration as a function of distance and frequency, or at least set upper limits for the listed external sources. Some of these sources may have already been characterized (paper study), some may need to be measured. In some cases, the vibration may be shown to be insignificant by direct analytical arguments.

Measure (or research) the vibration (force spectrum) from the listed NLC vibration sources. Of special interest (and difficulty) is vibration induced by flowing helium. Study the relative vibration from normal, super fluid, and pressurized super fluid (cooled below boiling with a heat exchanger and pressure head) liquid helium.

Measure the transmission of vibration through the ground. Use a known force generator, and measure the vibration at various distances and frequencies.

Supports:

While the overall design problem for the system feedbacks and supports contains a large number of interactions, there are several parts which can be studied independently. The design of supports and feedback are often closely related, and need to be considered separately.

Supports: The mechanical performance of supports can be viewed as containing several terms.

Response to ground motion: Response as function of frequency
Response to forces applied directly to the device (water, etc.): Response as function of frequency
If there is a feedback system: Response of the actuator and device to a feedback signal.

The optimization of the design of the system is related to the expected performance of the feedback system and to the vibration spectra, but we can make some general comments on the design.

Internal resonant frequencies: The internal resonant frequencies of the support and supported device should be as high as possible. This reduces the excitation of internal modes.

Damping: Damping of internal modes should be as high as possible.

Low frequency roll off: It may be desirable to roll off the response of the support at low frequencies to allow for easier operation of the feedback system.

The design of supports basically divides into two parts:

**Materials selection**: The stiffness, creep, and dynamic damping of structural materials varies widely. These properties need to be researched, or measured for small amplitude vibrations in our frequency range. Note that the damping of materials may be significantly different for low amplitude motions than for large amplitude motions. Thermal expansion of materials is generally well characterized, and additional research is probably not required. Creep data is also available for a large variety of structural materials. Some measurements of creep may be required for exotic materials (permanent magnet materials for example). Radiation induced changes in materials properties also need to be studied.

**Engineering Design**: Most standard engineering vibration control is concerned with large amplitude vibrations. It is not clear that standard vibration control practice applies to nanometer scale motions. For example the use of bolted (rather than welded) connections is known to increase the damping of engineering structures due to energy absorption from slipping in the joints. This damping mechanism will probably not apply to small scale motions where there is no slippage.

**Projects**:

Compile a list of materials properties, including stiffness (literature), creep (literature?), and damping for small amplitude motions (may required experiments). Properties need to be in engineering units suitable for incorporation into ANSYS or similar code. In addition to standard structural materials (steel, Aluminum, etc.), properties of high damping materials (lead, Manganese alloy, Anocast™), are required.

Evaluate the dynamic performance of the feedback movers (damping, stiffness, internal modes). Improve performance if possible.

Design and test a complete quad support. Compare performance with predictions.
Feedbacks

The stability of the component positions can be improved with active feedbacks. We can divide these type of feedbacks by their operating time scales

**Alignment**: Very slow (<1 / minute) feedbacks using movers. These systems would look at beam measurements (for example dispersion), and then adjust component positions. Some of the measurements will be invasive (e.g. most beam based alignment schemes), but an effort needs to be made to make measurements non-invasive. These feedbacks are typically removing long term creep and drift effects.

**Slow Feedback**: These feedbacks operate well below the 120 Hz beam rate. They typically use BPM data. The actuators do not need to operate on every pulse. They typically do not have mechanical dynamics issues.

**Fast Feedback**: These feedbacks operate at near the 120Hz beam rate. They typically use BPM data. The actuators need to operate at full beam rate, and mechanical dynamic issues are important. Interactions with other Fast and Very Fast feedbacks are a serious issue.

**Very Fast Feedback**: These feedbacks use accelerometers, or similar inputs (or beam data in the Damping Rings) to operate at rates from 120Hz to many KHz. The critical issues are dynamics and integration with beam fast feedbacks.

**Ultra Fast Feedback**: These are feedbacks which operate within a pulse train. The IP intratrain feedback is an example. These time scales are sufficiently faster than for other feedbacks that interactions are not a significant issue. These can reduce vibration sensitivity at the IP by a factor ~5.

All Feedbacks contain three basic elements: Sensor, Algorithm, Actuator.

**Sensors**: The performance of feedback sensors is relatively well understood.

- Stripline BPMs: These have been studied in considerable detail and are relatively well understood. Centroid drift is probably the least well understood parameter. For ultra-fast feedback the time delay of the BPM processing needs to be understood.

- Cavity BPMs: These have been studied in detail. Centroid drift is not well understood.

- Structure BPMs: Have been studied. Noise and drift need to be fully understood.

- Optical Interferometers: Well known commercial technology, also demonstrated by experiments at SLAC. Sub nanometer performance (in vacuum). Operation in air has been shown to be acceptable for short time scale measurements.

- Accelerometers / geophones: Well known commercial technology. Can have sub nanometer sensitivity at frequencies as low as 1 Hz. Commercial units will not operate in strong magnetic fields.
Electrostatic sensors can have sufficient sensitivity (tested at SLAC). Low frequency units are large. For high frequencies (>10Hz), units are simple and compact.

**Algorithms:** The processing of sensor data for feedbacks is an entire engineering discipline. It has been studied at SLAC for the case of discrete, beam based sensors, but not for more complex systems containing multiple sensors with varying data rates, and with multiple internal modes.

**Actuators:** A variety of actuators are available. Performance is well understood.

Magnets: Beam steering feedbacks may use corrector magnets. The performance of these is fairly well understood. Studies of the effects of shielding by the beam pipe need to be completed.

Movers: Motorized positioners. These have been demonstrated at the required <100nm resolution. Dynamics need to be understood. Various motor / sensor options to reduce cost need to be considered: Stepper motors, Servo motors, Acoustic motors, Piezo motors.

Piezo Actuators: These are well understood. Provide limited range (5µm to ~100µm), with essentially arbitrary resolution (used in gravity wave experiments at <<10^{-12}M). Applied force changes at electronic speeds. Disadvantage is high stiffness (can couple vibration from the support to the isolated system). Operate at cryogenic temperatures. Various similar materials are available: Piezoelectric, Electrostrictive, Magnetostrictive, etc.

Magnetic coils: Well understood, but less commonly used than piezoelectrics. Provide a force which can be varied on electronic time scales. Provide very low stiffness. Will not work in high magnetic fields.

Electrostatic actuators: Well understood (but not tested). Provide a small force which can be varied on electronic time scales. Provide very low stiffness. Work in high magnetic fields. Maximum force and range are small.

Inertial feedback: While most mechanical feedbacks are designed to produce force relative to the support, it is possible to use an inertial reaction mass for AC feedbacks. This provides additional flexibility in the design of the support system as the feedback will not excite modes in the support structure.

Fast kickers: For ultra-fast feedback high speed (nanosecond) kickers will be used. The primary issue is the time delay in the high power amplifier chain to drive the kickers.

**Integration Issues:** While each of the components of feedback systems are fairly well understood, there are significant integration issues. The combined design of supports, sensors, actuators, and feedback algorithms is a complex multi-disciplinary problem.

**Projects:**
BPM stability: Do tests to understand the centroid drift of the various BPM systems. If the BPM electronic to mechanical centroid drift can be controlled to <1µm, the alignment procedure can be greatly simplified. BPM studies are underway.

Optical Interferometers / Accelerometers: The performance of these is well understood. Some integration issues may need to be examined.

Feedback algorithms: We need an expert on feedback systems on this project.

Feedback processor design: The “very fast” feedbacks will required a special dedicated processor. Develop a system (possibly a real time box with matlab control) for very fast feedback. Not that this box can also be used to test standard slow and fast feedbacks.

Beam pipe shielding: Some calculations have been done on shielding of high frequency magnetic fields by the beam pipes. These need to be completed, and possibly compared with an experiment.

Inertial reaction mass feedback: A simulation and possibly experimental test of reaction mass feedback should be done.

Ultra-fast feedback: An end to end ultra fast feedback system electronics test should be constructed.

Integrated mechanical test: A full mechanical feedback system, suitable for use on a linac quad, should be constructed. This is a relatively simple model, but will allow the study of various system integration issues. In addition, it may be practical to add an active feedback system to the actual linac quads.

**Final Focus System**
The final doublet is in many ways the most difficult vibration problem in the NLC:

- Tightest vibration tolerance in the machine: ~1nm RMS.
- Mounted in an area with very restricted access (inside the detector).
- A “long thin” structure, with fairly low frequency (~50Hz) internal resonances. This complicates potential feedback systems.
- Located in a strong magnetic field - eliminates some measurement and actuator technologies.

A variety of engineering issues are being considered for the final focus support and stabilization system:
Support tube: A mechanical design for the support tube is underway. The design is intended to produce a very rigid structure with high internal mode frequencies (relative to its length and aspect ratio). The present design is not designed with reference to a fast feedback system.

Magnets: It is desirable from the point of view of vibration to use permanent magnets, however the final focus design may require super conducting magnets.

Optical Anchor: Uses an optical interferometer to measure the distance from the final focus to the ground. This system can provide low noise fast position data. It relies on their being small differential ground motion under the doublets. System requires optical pipe access through the detector. Tests have been done at SLAC, and are underway at (....). on the interferometer, and it is now well understood. The primary technical issues are understanding the differential ground motion (including cultural noise!), and system integration issues.

Inertial Anchor: Use one or more accelerometers to measure the doublet vibration. These would need to be custom electro-static, rather than magnetic accelerometers.

The viability of high sensitivity electrostatic accelerometers has been demonstrated.

Ultra-fast Feedback: Simulations indicate a substantial reduction in jitter sensitivity.

Projects:

Complex object stabilization: Use an object with complex internal resonances, and a structure similar to the final focus doublet support, for example an Aluminum I-beam. Using various sensors (accelerometers and interferometers), and actuators (piezo or magnetic) close a feedback loop. Use this to understand the validity of feedback simulations, and to understand real-world problems.

Final focus mock-up: Construct a final focus support tube that will have mechanical properties similar to the final system. Non-magnetic blocks can be substituted for the permanent magnet materials. Alignment tolerances do not need to be maintained. Then use this system to test various feedback systems.