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WEAPONS SIMULATION TRACKING SYSTEMS (TESTING METHODS)

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As small arms weapon simulation systems are increasingly employed by military and law enforcement agencies, requirements and specifications for weapon tracking systems need to be addressed. The integration of weapon tracking systems is hampered by a lack of standardized methods for their testing and analysis. This report documents suggested standardized test procedures for evaluating position/orientation tracking systems relative to their ability to perform in Weapons Fire Simulators. Discussions are provided on tracking system basics including: the terminology used in tracking systems, the different tracking types and technologies, and weapon fire simulation requirements. A computer controlled motorized linear track was used to evaluate performance characteristics of weapon tracking systems. The evaluation discussion includes: the definition of the parameters to be tested, the equipment and procedures to be used, and the analysis of the data recorded. Data is collected to evaluate the parameters of resolution and accuracy for both position and orientation. Two distinct weapons tracking cases are tested for accuracy: static and dynamic. These two cases evaluate a tracker's use in marksmanship training, where the weapon is barely moving, and tactics training, where the weapon is moving at moderate to high angular and translational rates. Procedures are provided for each test, describing the data to be collected and the calculations to be performed. These procedures have been integrated into a tracker test program that collects the data while controlling the test track and tracking system. Appendices are included that provide an overview of the tracker test program, a sample test plan, and sample tracker test program outputs.

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EXECUTIVE SUMMARY

INTRODUCTION

Small arms weapon simulation systems have been successfully applied by the Navy, Marines, Army, Air Force, Special Forces, and other military, as well as, law enforcement agencies within the last fifteen years. These systems have been both training and cost-effective in addressing their simulation needs. However, as weapon simulation systems move into the realm of complex virtual worlds, new demands and requirements for weapon tracking systems are occurring. These tracking systems are an important part of a weapons fire simulation system. They provide the link between the trainee, his weapon, and the simulated weapons range and targets. In many applications of weapon tracking systems, a lack of understanding of the available tracking technologies and their specifications has led to disappointing performance and limited training. Use of tracking systems requires that the tracking system performance parameters be specified for the weapons fire simulation task and verified to meet the specifications.

OBJECTIVE

The objective of this report is to provide documentation on an effort to create standardized test methods for tracking systems intended for use in weapon fire simulation. The effort detailed in this report is a first step in providing a documented measurement procedure for candidate tracking systems. The parameters of resolution and accuracy for both position and orientation measurements are the principle interest of this effort. The goal is to identify tracking systems that can be incorporated into weapons fire simulation systems without introducing negative effects on the training task.

APPROACH

A linear motion servo-controlled track system is used to provide computer controlled motion of a tracked target. Computer software was written to activate the tracking system, control the track movement, collect tracking data, and calculate tracker performance statistics. Resolution and accuracy tests are performed, with accuracy tests performed in both a static and dynamic manner. Statistical output data is available in tabular format and can also be used to graph the tracking errors during target movement.

CONCLUSIONS

The tracking test software and linear motion track provide a means to analyze the real time position and orientation output data from a tracking system. The use of the linear motion track provides relative position information that serves as a reference for the target position and movement. The collection and statistical analysis of the data for resolution and accuracy allow a view of a tracking system's performance that has not been previously independently available. Statistical and graphical data output from the software program can be used to determine if a tracking system meets the requirements of the weapons fire simulation task.

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INTRODUCTION

The purpose of this report is to document test procedures developed to evaluate position/orientation tracking systems for their ability to perform in Weapons Fire Simulators. This work was performed as part of the Advanced Weapons Simulation Technology (AWST) task conducted at NAWCTSD.

Tracking systems are now available as commercial off-the-shelf equipment from many manufacturers. The basic task of a tracking system is to provide the position and, in some cases, orientation of an object. This data is intended to be used in a simulation computer system to allow an object's position and orientation to be specified relative to a known database. Two or three dimensional position data and angular orientation data is supplied in digital form to the simulation computer. If the object tracked is a viewer's head, the simulation computer can take this information and use it to provide a view of a terrain database for a particular viewpoint and viewing direction. For weapons firing purposes, where the weapon is the tracked object, the tracking information is used to determine where the weapon aimpoint intersects the database.

Selecting a tracking system includes the following steps: understanding tracker terminology, identifying available tracker technologies, and determining if the tracker performance meets the requirements of the simulation task. The first two steps are difficult due to the complexity and number of tracking system designs. Performing the first two steps is also difficult because the different technologies employed have distinct features requiring independent terminology and usage. The lack of standardized terminology, specifications, and testing methods for weapon tracking systems and a lack of understanding of the overall error budget for weapon fire simulations complicates the third step. Numerous error sources from the individual simulation system components can accumulate and lead to a poor overall error budget for the total weapon tracking system. Assuming that the tracking requirements are known for a simulation task, determining which tracking system has the ability to perform within the requirements is a formidable task.

To thoroughly specify and integrate a weapon tracking system, the user must have an in depth knowledge of the overall weapon tracking / simulation application. To provide background knowledge for selecting a tracking system, this report provides discussions on: the terminology used in tracking systems, the different tracking types and technologies, and weapon fire simulation requirements.

Testing apparatus was constructed for evaluating some of the performance characteristics of weapon tracking systems. This system incorporates a computer controlled motorized linear track. The linear track uses optical encoder technology to provide feedback to a servo-controller for highly accurate positioning and position output of a moveable stage. The track encoder output is used in determining a tracking system's output position accuracy. This report discusses methods and software developed for testing and documenting the performance of tracking systems using this linear track. The evaluation of tracking systems includes: the definition of the parameters to be tested, the equipment and procedures to be used, and the analysis of the data recorded.

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TRACKING SYSTEM BASICS

An important step in evaluating tracking systems for use in weapon fire simulation is to understand what tracking systems provide and how their performance is specified. In this section information is provided on tracking system terminology, types of tracking systems, and the technologies used in tracking systems.

TRACKING SYSTEM TERMINOLOGY

The definitions in this section are for terms as they are applied to tracking systems. To provide an insight into the usage of these terms, some discussion of each term is also included. A problem with many of the terms commonly used to specify tracking system performance is that the definitions are based on data collection techniques that are not well defined, or not defined at all. Each tracking technology has its own unique features related to its performance capability, with selective use of features affecting specifications. There may also be specific advantages and disadvantages related to the technology used in the system. The intent of this section is to discuss the definition of the terms so that each tracking system's specifications may be compared equally. Some of the terms in this section may not be used in this report, but are included for general information purposes. Note that some of these tracking terms are also used in other disciplines and may have totally dissimilar meanings.

<u>3D Coordinate System</u>

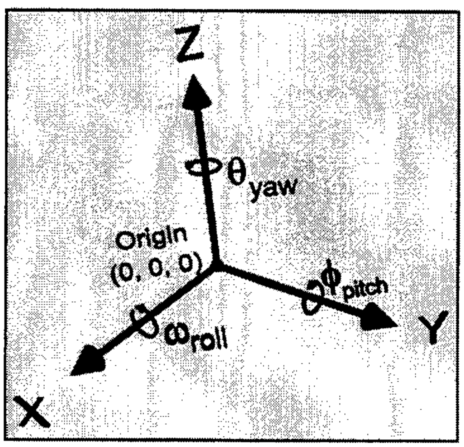

Figure 1. 3D Coordinate System.

A 3D coordinate system is a reference system for three dimensional space that provides a framework for position and orientation descriptions. There are 6 Degrees Of Freedom (DOF) associated with a 3D coordinate system (see DOF term). Figure 1 shows the 3D coordinate system, which is defined by an origin and a set of three orthogonal axes. The three axes represent the X, Y, and Z dimensions of space with the origin defined as the (0,0,0) position. Various schemes are used to define which axes represent the up/down, right/left, and forward/backward directions. The forward axis (positive direction) may also be referred to as the major axis. Each use of a coordinate system should define the assignment of these directions, including the polarity (+/-) of the axis relative to the direction. This coordinate system also allows for definition of angles of rotation about the axes or orientation of objects within the coordinate system. These angles are typically named yaw, pitch, and roll. By convention, yaw is a horizontal rotation about the up/down (or vertical) axis, pitch is a vertical rotation about the left/right (or horizontal) axis, and roll is a rotation about the forward/backward (or major) axis. The assignment of the rotation angles to the axes and the direction of positive and negative rotation should be defined due to the many different schemes possible.

Accuracy (See also: Static and Dynamic Accuracy)

Accuracy is the extent to which a given measurement agrees with a known or standard value for that measurement. Accuracy is a qualitative term used to express the probability that a measured value matches the actual value (Taylor, 1994). Any difference between the measured value and the actual value is defined as the error. Accuracy is calculated by taking the standard deviation of the error derived from a set of samples. Accuracy provides an indication of the quality of data output in absolute measurement units. Accuracy values are expressed as a quantitative error value plus an indication of the quality of the accuracy value. This qualitative term is generally expressed in units of standard deviations, where 1, 2, and 3 standard deviations correspond to instances where all data samples fall within the quantitative error plus or minus the qualitative value approximately 68%, 95%, and 99% of the time, respectively.

For tracking systems, accuracy is the ability of the tracker to provide the exact measurement of position or angle for the object being tracked. Accuracy values are usually specified by manufacturers as a single number such as 0.1 mm or 0.3 degrees. Investigation into manufacturers' methods of calculating accuracy have determined that most are quoting the error between the Root Mean Square (RMS) of a number of data samples and an absolute or relative position/angle reference. It should be noted that these data samples are generally taken with any noise filtering available in full operation, which tends to reduce system noise. This filtering may involve an averaging of several data samples leading to increased time lag and reduced dynamic response. Averaging of data samples can only be useful when the tracked target is stationary and would not be appropriate for target motion. Turning off filtering would tend to significantly increase variations in the data output, leading to lower accuracy (larger error values).

Degrees Of Freedom (DOF)

Degrees Of Freedom refers to a tracker's ability to measure the position and orientation of an object in space. For tracking systems, there are three common DOFs of interest: 2DOF, 3DOF, and 6DOF. A 3DOF system measures target position in 3 dimensional (3D) coordinates position only (i.e., (x, y, z)), while a 2DOF system provides a less descriptive 2D coordinate set (i.e., (x, y)). A 6DOF system provides the total data set of 3D (x, y, z) position and orientation angles (yaw, pitch, and roll) about the three axes of the coordinate system. See Figure 4 for an illustration of a 3D coordinate system and orientation angles.

Drift

Drift is a low frequency variation in a tracker's output data, often due to instability of the sensor and/or the tracker electronics. Drift is specified in terms of the change in the data value magnitude along with the frequency of the change.

Emitter

The producer of the signal received by the sensor is the emitter. The emitter/sensor pair are generally a matched set where the output profile of the emitter corresponds to the input response of the sensor. The emitted signal depends on the technology used in the tracking system and may be visible light, infrared radiation, acoustic sound waves, magnetic fields, or radio-frequency waves.

Field Of View (FOV)

FOV refers to the angular extent that a tracking emitter/sensor pair can "see" each other. Depending on the sensor type, FOV may be specified in terms of the horizontal and vertical angles across the midpoint of the sides of a quadrangular pyramid (4 sided, rectangular base pyramid); as an angle describing the diagonal angle for the same pyramid; or may be given as an angle, or half-angle, across the base of a conic projection.

Jitter

Jitter is a high frequency variation in a tracker's output data, often due to environmental interference or instability in the tracker electronics. Jitter is specified in terms of the change in the data value magnitude along with the frequency of the change.

Lag (or Latency)

Lag is the time difference between the start of a tracker measurement at a position in space and the output of the data for that position. Lag becomes important when the tracked object is moving. During movement, the data output values are for the target position one lag period back in time. Depending on the lag time and the rate of movement, this offset can add significant error to the position data. If the lag period is known and fixed, compensation methods may be used to reduce errors due to lag.

Line Of Sight (LOS)

Line Of Sight refers to an unobstructed path between a tracked target and tracking sensor. In a tracking system, the LOS must be maintained. If an object blocks this direct path, tracking is interrupted.

Marker (See Target)

Motion Volume

Motion Volume is the 3D volume space within which a tracking target can detected. The volume may be described in terms of a rectangular or cubic volume with specifications for length, width, and height. The motion volume is sometimes defined in terms of a FOV and a distance relative to the tracking head. The motion volume is actually limited by the combination of the acceptance angles of the receiver and the emission profile angles of the emitter. These angles are 3D conic shapes that may extend to complete spheroids. If the receiver/emitter angular profiles do not overlap, then contact will be lost and the target will not be properly tracked.

Orientation Angles - Yaw, Pitch, Roll

Yaw, pitch and roll are the names of rotation angles associated with rotation about the axes of a 3D coordinate system as shown in Figure 4. By convention, yaw is a horizontal rotation about the up/down (or vertical) axis, pitch is a vertical rotation about the left/right (or horizontal) axis and roll is a rotation about the forward/backward (or major) axis. In weapon simulation systems, the yaw and pitch angles are useful in specifying the orientation of a weapon's barrel. The roll angle is used to determine the weapon cant (defined as the angle of the weapon sight off the vertical (gravity) axis).

Origin

The Origin is the reference or home position of a coordinate system. For a 3D coordinate system, the origin is defined as (0,0,0). All coordinate system positions are measured in terms of displacement from the origin along each of the coordinate axes.

Output Rate (See Update Rate)

Pitch (See Orientation - Yaw, Pitch, Roll)

Precision

Precision is the smallest change in the data values that a system can output. For systems providing digital data output, precision is related to the number of bits of the analog to digital converters (ADCs) and the maximum measurement value allowed. However, in most cases one or two of the least significant bits (LSBs) will exhibit random variations consistent with system noise effects. These noise variations are in no way related to actual movement of a tracked target and, therefore, those bits are not a measure of system resolution. A hardware system which outputs values with a 16 bit number of which the last two bits fluctuate randomly can be said to have 16 bits of precision, but a maximum resolution of only 14 bits.

As an example, consider a tracking system that outputs (x, y, z) position data in integer values from via a 16 bit ADC. The 16 bits for each data value allows the maximum output value to be divided into 65,536 parts. If the maximum range of the tracker is 6.5 Meters, then the assignment of each bit of the 16 bit word makes a change of 1bit (1/65,536) equal to 0.099 millimeters. The system precision is 0.099 mm since that is the smallest change that the system can indicate. If there are two LSBs of noise in the output, the effective output is a 14 bit value, and the system resolution is 0.397 mm (6500 mm/16,384).

Note that when representing this value in software, the variable type used to store the value may reduce the precision.

Range (or Motion Range)

Range is the distance between the tracking receiver/emitter pair over which the tracking system can operate. The maximum range is the longest receiver/emitter distance over which a receiver/emitter pair can operate. The minimum range is a function of the FOV of the receivers and the emission profile of the emitters, such that the receiver can detect the emitter. Generally, when the emitter is outside the motion range, the tracking system loses contact and generates data errors. This can cause serious changes in the data output, instead of performing a gradual reduction in data reliability. After the tracking system loses contact with the tracked target, it may have difficulty in reacquiring the target.

Resolution

Resolution is the smallest increment in a tracker's data output values that represents a statistically significant minimum change between two positions or orientations of a tracked target. This change in output is related to an actual movement of the target, not output changes associated with noise. In other words, resolution answers the question, '*What is the minimum change in the data output that indicates that the target has actually moved?*'

There should be a resolution specification for position output (in inches or millimeters) for 3DOF trackers; and additionally, for orientation output (in degrees) for 6DOF trackers. With most systems providing digital data output, the resolution specifications may be related to the maximum range allowed and the number of bits of the analog to digital converters (ADCs). A system with 16 bit ADCs operating at a maximum tracking range of 6.5 meters would break the 6.5 meters (6500 mm) up into 65,536 parts, or 0.099 mm. If the operating range is reduced to 1 meter (1000 mm), then each of the 65,536 parts would represent 0.015 mm. This relationship of measurement distance to number of bits actually provides a measure of precision, which is not a reliable indicator of resolution.

Roll See Orientation - Yaw, Pitch, Roll

Sample Rate

The sample rate is the number of samples per second that each individual target is sampled. The inverse of the sample rate is the sample period (the number of seconds between the target sampling). The output of the data related to this sample may occur within one sample period, but may occur after one or more sample periods.

Sample Time

Sample Time is the time that the target information is actually being gathered. This time is important when a target is moving. Long sample times allow the target to move significantly between the start and end of the target sampling. Sample time is usually not available to the user since it is internal to the tracker system.

Sensor

In the broadest terms, a sensor is a receiver of a signal. A sensor is used in a tracking system to receive a signal that is used to interpret the position/orientation of the object being tracked. Sensors are designed to receive signals that are provided by emitters, or signals that are derived from natural sources. Types of sensors include: optical, magnetic, acoustic, mechanical, inertial, radio-frequency, gravitational, etc. Note that some of these types of sensors have further sub-types that indicate a narrowing of their sensing ranges. For example, optical sensors operate in limited portions of the electromagnetic spectrum, where one subtype will only respond to visible light near 680 nanometers wavelength and another to near-infrared radiation about 880 nanometers. Another example is inertial sensors, where one sensor can respond to accelerations up to one unit of gravity ($1G = 9.8\ m/s^2$) before saturation, while another may be able to respond up to 5G.

Speed of Sound

For ultrasonic tracking systems, the speed of sound is a limitation. Depending on the acoustic target and receiver separation, time of flight of the acoustic pulse limits the maximum sample rate for the system. The speed of sound varies with environmental factors such as temperature, pressure, and humidity. For example, at 0 Celsius in air, the speed of sound is given as $V_0 = 331$ meters/sec. Variation due to temperature is: $V = V_0\,(T / 273)^{1/2}$, where $T = (273 + C)$ is absolute temperature in Kelvin. At 25C (77F), V = 345.8 m/sec, or 345.8 mm/msec. At this velocity, a sound wave would take 5.78 milliseconds to travel 2 meters (2.89 msec/meter), which is a significant portion of time when compared to typical sample rates of 30 to 60 Hertz.

Target (or marker)

A target is the object that the tracking system is actually tracking. One or more targets are usually attached to other, larger objects (e.g., a person, weapon, or robotic device). There are two types of targets: active and passive. Active targets emit a signal (e.g., LED, acoustic spark gap) that is detected by a receiver. Passive targets, usually associated with optical systems, do not emit their own signal, but reflect a signal, usually visible or near-IR energy.

Throughput Delay

Throughput delay includes the tracking system latency time and the additional time required for the system receiving the tracking data to provide an output based on the tracking data. In the case of a visual display using tracking information to generate perspective imagery, the throughput delay is the time from start of tracker measurement to start of the output of an image based on the tracker data.

Update Rate (or Output Rate)

The update rate is the number of tracker data groups output per second (expressed in Hertz) that are available for use in a simulation. This is the frequency of updating the set of targets being tracked by the system. When specifying the update rate of a tracking system the following information for the data output group should be provided: the type of data (3DOF, 6DOF, etc.), the number of targets being tracked, and any noise filtering options used. Note that the position and orientation targets may be sampled at a rate higher than the update rate, with several samples combined mathematically for a single output at the lower rate. This sample rate/ update rate scenario is usually associated with predictive or filtering algorithms.

Yaw See Orientation - Yaw, Pitch, Roll

TRACKING SYSTEM TYPES

Tracking systems can be described in two ways. One description is based on the number of Degrees Of Freedom (DOF) in the output data. The other is based on the location and arrangement of the sensors and sources used in the tracking system.

Degree of Freedom Classifications

There are three primary output formats for weapon tracking systems: 2DOF weapon aimpoint tracking, 3DOF weapon position tracking, and 6DOF weapon position/orientation tracking. Each of these types of weapon trackers has inherent features which can be considered an advantage or disadvantage depending on the particular application. For weapons fire simulation, the arrangement of tracking system components depends on the DOF of the tracking system. Depending on the DOF, the initial conditions for flying a projectile are either provided directly by the tracker or calculated from the available tracker data and its configuration.

2DOF Weapon Aimpoint Tracking Systems. Figure 2 depicts a typical setup for a 2DOF tracker. A 2DOF weapon tracking system provides a 2 Dimensional (2D) aimpoint for where the weapon vector intersects the visual display. A simulated weapon is typically instrumented with an aimpoint indicator such as a collimated infrared (IR) source. The source, mounted to the barrel of the simulated weapon, projects an infrared spot onto the surface of a large display screen to indicate the weapon aimpoint. The infrared source reflects off the display screen and is detected by a spot tracker. The weapon tracking system then determines the trainee's aimpoint relative to the 2D display system screen coordinates. In operation, the position of the weapon barrel is fixed within a relatively small area at a distance D_{2D} of approximately 10 to 15 feet from the screen. A weapon vector W, representing the boreline of the weapon, is calculated from the 2D aimpoint coordinates relative to a default weapon location. The yaw and pitch angles of the weapon vector are used to extend the aimpoint into a 3D database. This 2DOF approach, while providing only 2D weapon aimpoint information directly, has been shown to provide the most accurate and stable aimpoint data for weapons fire simulation systems. The large distance, D_{2D}, combined with a small linear aimpoint error

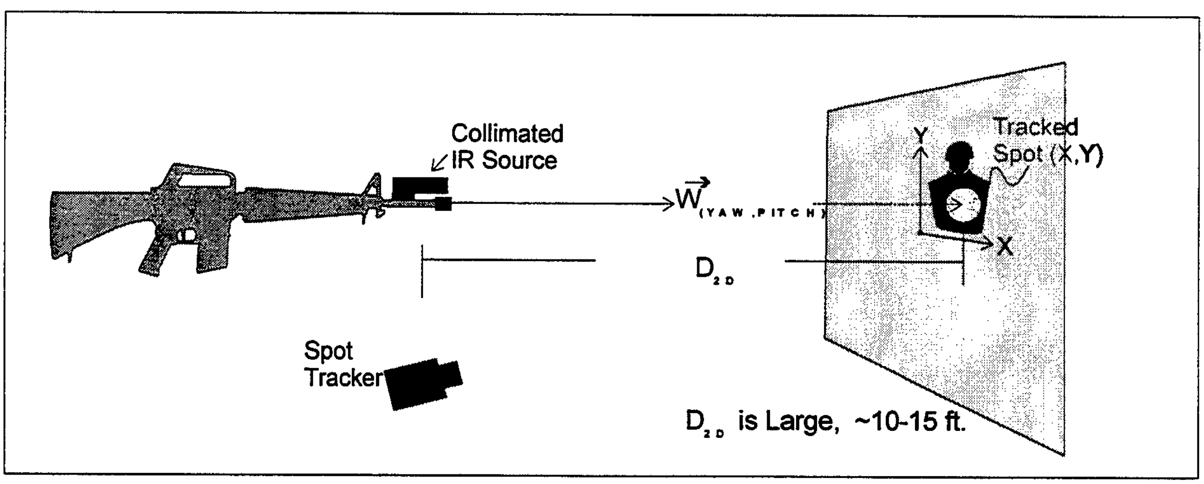

Figure 2. 2DOF Tracker Configuration.

provides for potentially small angular errors in 2DOF trackers. Currently, the 2DOF weapon tracking system is the most accurate of the three primary tracking technologies. Although numerous technologies are available, the most common 2D weapon tracking systems are primarily based on optical technology and are limited to line of sight applications.

3DOF Weapon Position Tracking Systems. 3DOF weapon tracking systems are being used to address the limitations of 2DOF tracking systems. A 3DOF weapon tracking system, as shown in Figure 3, can provide both position of the weapon and the weapon vector, W. The weapon barrel position, Tgt_B, is a direct output of a 3DOF tracking system. The weapon vector is calculated by using the 3D position coordinates from two tracked targets on the weapon (i.e., on the barrel and stock). Using this weapon vector, the aimpoint into the database can be found by projecting the vector into the synthetic environment. The 3DOF approach, although typically not as accurate as the 2DOF approach, has the capability of providing the 3D weapon aimpoint through use of the barrel position and weapon azimuth (yaw) and elevation (pitch) launch angles. The simulated projectile path from the simulated weapon is based on the 3D barrel position and orientation rather than simply the 2D weapon aimpoint on the display screen. Note that for small arms weapons the distance between the two tracker targets mounted on the weapon is relatively small, resulting in significant orientation errors from minor target position errors. 3DOF weapon tracking systems are typically based on ultrasonic or optical technology that are limited to line of sight applications.

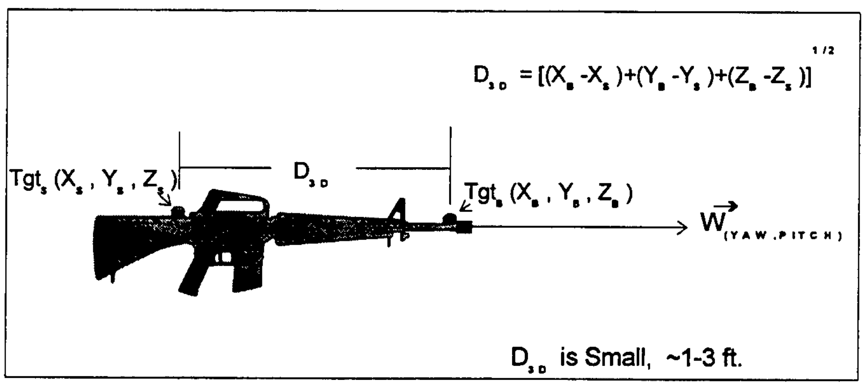

Figure 3. 3DOF Tracker Target Configuration.

6DOF Weapon Orientation Tracking Systems. 6DOF tracking systems provide a complete set of weapon position and orientation data directly. In a 6DOF tracking system, a single 6DOF sensor (or sensor set) provides 3D position coordinates as well as yaw, pitch, and roll angle information relative to a reference coordinate system. Figure 4 shows the tracker target mountings for a hybrid 6DOF tracking system, where an inertial sensor provides the orientation data while an ultrasonic target provides position data. This direct output allows the flight of the weapon projectile to be based on weapon position and orientation (same as the 3DOF type, but adds the roll or cant angle), while reducing orientation processing by the simulation computer. 6DOF trackers typically offer some ability to avoid Line Of Sight (LOS) restrictions, but suffer from poor accuracy when compared to the 2DOF and 3DOF technologies. 6DOF tracking systems are typically based on magnetic, optical, or hybrid technologies (i.e., inertial and ultrasonic). A high accuracy 6DOF weapon tracking system, if developed, would provide the ultimate weapon orientation tracking solution.

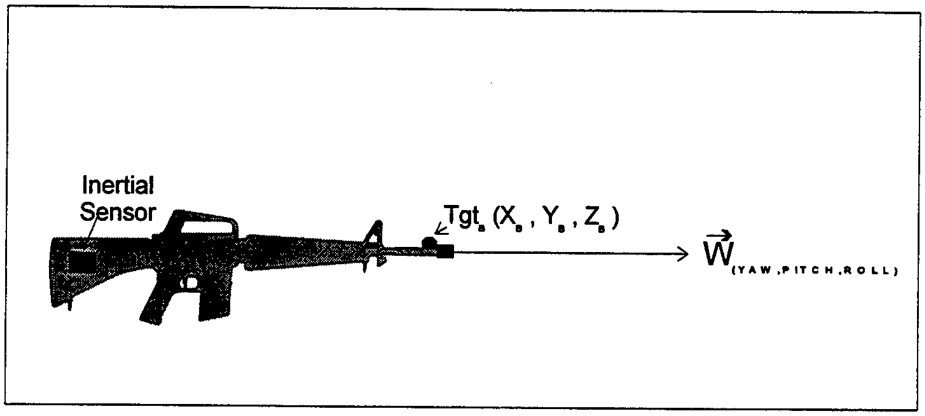

Figure 4. 6DOF Tracker Target Configuration.

Inside-In, Inside-Out, and Outside-In Tracker Classifications

This method of classifying tracking system types is based on the arrangement and method of using the sources (emitters) and sensors involved in the tracking process. Tracking systems have been generally described as one of three classes that include: Inside-In, Inside-Out, and Outside-In systems (Mulder, 1994). These tracking system classifications are based on the location of the source and receiver systems relative to the tracked object and the environment. The classification label is made up of the sensor location followed by the source location. A sensor attached to the target is described as "Inside," while a sensor located within the environment is described as "Outside." A source attached to the target is described as "In," while a source located in the environment is described as "Out." In some cases, the distinction between the classes is hard to make, and in others a combination of the classes have been used to make a tracking system.

Inside-In Tracking Systems. Inside-In tracking systems have both the sensor and source attached to the tracked object. Examples of Inside-In trackers include the data gloves and other self-contained systems that use small sensors. Generally these tracking systems are used to capture individual body movements (e.g. fingers, arms, legs) in an angular fashion. Advantages are a large motion box, freedom from environmental interference, and ability to provide high resolution. Disadvantages are that they are physically restrictive, involve a long setup time, require many tether cables, and generally do not provide 3D positional data due to a lack of a 3D reference.

Inside-Out Tracking Systems. Inside-Out tracking systems have a sensor attached to the target that senses a source located in the tracking environment. Sources may be artificial (i.e., electromagnetic fields from three axis coils, or LEDs that are ceiling or wall mounted) or natural (i.e. earth's gravitational or magnetic field). Advantages of Inside-Out trackers are small to medium form factor for the tracked targets, ability to provide 3D and in some cases 6DOF information, medium to high speed sample rates, and lend themselves to wireless operation allowing freedom of movement. Disadvantages may include small to medium motion box due to limited source strength, and low to medium resolution/accuracy.

Outside-In Tracking Systems. Outside-In tracking systems involve the use of externally mounted sensor systems that track active or passive emitters or markers attached to the tracked object. These markers may be retroreflective discs or spheres, or near-Infrared (near-IR) or visible LEDs. This general class of tracker includes most of the optical types. One optical tracker example uses an illumination source at a camera head(s) which is retroreflected off passive markers and back to the camera. Other optical systems use active sources as the target marker (LEDs) that provide their own illumination. Advantages include: very small tracked targets that make Outside-In trackers the least obtrusive of tracking systems and may allow many markers to be simultaneously tracked, medium to high resolution/accuracy, and ability to expand the motion box coverage by adding additional camera sensors. A major disadvantage is a problem dealing with interruptions of the Line Of Sight (LOS) between the markers and camera sensor. When LOS is lost, the tracking solution breaks down, and reacquiring the targets takes time during which the target information is unavailable. Other disadvantages are that they may require extensive setup, use complicated processing algorithms for performing the tracking and maintaining target lock (especially after loss of LOS), and typically use specialized optical devices and computer hardware and software that make the tracking systems expensive. For medium to large motion boxes, multiple camera sensors integrated into the system further increases the cost.

For Weapons Fire Simulation and in the interest of obtaining three to six DOF tracking data, the Outside-In and Inside-Out tracking systems are of the most interest. Ideally the targets should be very small for mounting on a weapon without interfering with its operation. Medium to large motion boxes are preferred to allow movement of the weapon and the trainee. Some tracking technologies of interest and their classifications are:

Technology	Classification
Acoustic	Outside-In
Inertial	Inside-Out
Magnetic	Inside-Out
Optical	Outside-In

TRACKING SYSTEM TECHNOLOGIES

Tracking devices are commercially available using opto-electronic, acoustic/ultrasonic, mechanical, inertial/accelerometer, and magnetic technologies. A new technology is radio frequency (RF). Each tracking system technology has their own set of characteristics based on the sensor/emitter technology. In general, these characteristics determine how a tracking system is designed and how well an object can be tracked. Some of these technology dependent parameters include: tracking speed, range of tracking, number of degrees of freedom tracked, number of targets tracked, resolution, accuracy, field of view, and data latency. Whichever tracking technology is selected, it is imperative that the user understands the specifications and limitations as it applies to the application and requirements.

Opto-Electronic

Optical tracking systems involve the use of optical sensors (Position Sensing Detectors (PSDs), Linear Array Charge Coupled Devices (CCDs), 2D Array CCDs, etc.) and special target(s) (retroreflective & active emitters) to be tracked. Optical tracking systems are generally set up for 3 Degrees Of Freedom (DOF) providing the 3D (x, y, z) coordinates of the target. Some trackers have optional active targets that are fixed in a rigid body structure and are intended for providing the additional yaw, pitch and roll angles for full 6DOF. There are two basic variants of optical tracking devices used in 3DOF/6DOF tracking; Outside-In and Inside-Out.

In the first variant (Outside-In), targets are fixed on the object to be tracked and sensors are mounted externally looking at the targets. Sensor output is used to perform 3D triangulation. Targets used by these systems include passive retroreflectors and active sources. The retroreflectors, generally glass bead coated, are illuminated by a pulsed source located near the sensor's imaging lens for maximum retroreflection. These sources usually operate in the invisible near-IR wavelength, but may be a visible red color. For cases of multiple passive target tracking, identification of the targets is accomplished by use of different shaped targets, by software algorithms, or manually. Active targets are LEDs that may be pulsed sequentially or individually modulated for purposes of identifying which target is being tracked. Some systems use a wearable battery operated control unit to operate several active targets, while others use tethers that are connected to the control unit.

In the second variant (Inside-Out), a unique system for head/helmet tracking has been constructed. Sensors are mounted on the top of a helmet and a set of sources (i.e. infrared LEDs) are accurately placed above the sensor in ceiling panels. An example of this is the opto-electronic ceiling tracker, the Hiball, being developed at the University of North Carolina at Chapel Hill. In the Hiball, PSD sensors are mounted on a helmet.

In both cases the position and orientation of the tracked targets are computed by using the projections of the targets on the sensor image planes. For faster processing, a number of systems use Digital Signal Processors (DSPs) at the sensor to preprocess the image for the target 2D centroid coordinates before sending the data to a control unit, where data from all sensors are used to triangulate the 3D coordinates of the target.

In general optical trackers have high update rates and reasonable lags. They suffer from the line of sight problem, in that any objects between the source and the sensor will interrupt the system operation. Passive targets (retroreflectors) are not desirable for use in a real time simulation environment, due to the time involved in setup and problems in maintaining an accurate identification of targets in a multiple target scenario. Active targets that use a scheme for identifying each target are more desirable, with several trackers offering some form of tetherless active target controller.

<u>Acoustic (or Ultrasonic)</u>

Acoustic, or ultrasonic, tracking systems use high frequency (~ 40kHz) sound waves to track targets by triangulation using Time-Of-Flight (TOF) based on the speed of sound in air (331 m/s @ 0C, 345.8 m/s @25C), or by measuring the difference in phase between the transmitted sound and the received sound (phase-coherence). The triangulation method uses the sound wave's TOF between the tracked transmitter and several stationary receivers to determine distance from the tracked target to the receivers. In the phase-coherence method, the signal phase difference between the signal sent and that received is used to determine if the tracked object has moved and, if so, an incremental position is added to the previous position.

A common acoustic tracking method involves the use of an acoustic transducer (target) and three fixed position microphones to form a basic acoustic tracker (Outside-In). The target emits an acoustic "pulse" in response to an infrared trigger signal received from infrared LEDs located at each microphone. All three microphones (receivers) listen simultaneously for the sound signature. The timing of the signature yields the distance to each of the three microphones, which is then used to triangulate the 3D position of the target. Use of the infrared trigger signal makes the acoustic wave travel path one-way from the target to the sensors. However, a fast sample rate of 200 Hz. (5 msec.) would allow for less than a 1.5 meter measurement distance due to the sound wave's flight time (4.34 msec. for 1.5 meters) and subsequent triangulation calculations.

An Inside-Out version has been proposed, where a single microphone is the tracked target and multiple, precisely located transducers are ceiling mounted. The Inside-Out version requires that the electronics/ processing system be attached to the tracked object. Additional time lags will occur with the inside-out method, due to individual triggering of the acoustic transducers as the microphone searches and listens individually for those accessible.

The advantage of acoustic trackers is high resolution, with claims of up to 0.5 mm. in the X, Y, and Z dimensions; or, 0.1mm in any one dimension using phase coherence methods. Velocity and acceleration outputs are possible. The Outside-In version with its independent emitter, is available as a battery powered unit, allowing for unrestricted movement with no tethers or linkages. While the (x, y, z) position of a target is available directly, angular orientation data must be derived from two or more transmitters. Microphones must be mounted in a precisely measured fixture. The tracking volume is limited by the speed of sound and the measurement range cannot be enlarged by adding more receivers. Acoustic trackers require an unobscured direct LOS between emitter (target) and receivers, or data dropouts will occur. After loss of target communication, reacquiring the target may take many sample periods and require positioning the target well within the motion volume. Multiple tracked targets decrease the individual target sample time since each must be sampled sequentially. Additionally, acoustic transmitter ringing and reflected echoes can affect measurements, requiring a wait time for these effects to die out. Acoustic trackers rely on the speed of sound to determine distance. However, the speed of sound in air is affected by temperature, pressure, humidity changes, and localized air currents from ventilation systems. Latency is variable and dependent on distance being measured in addition to data calculation time. Ambient noise near 40kHz sound frequency and reflections off hard surfaces can also play a part in "confusing" the system.

Higher frequencies would allow better resolution, but atmospheric attenuation increases rapidly above 50-60kHz and would limit the range. The phase coherence method suffers from cumulative errors and at least one system can only operate in this mode if movement is along a single axis.

Mechanical

Mechanical tracking systems involve a physical connection to the tracked object and are referenced to a fixed position, such as a wall or floor. The physical connection involves a series of rigid links with interconnecting rotational and translational joints outfitted with devices that provide the angular and positional relationship of one link to another. Mechanical tracking systems can exhibit high resolution and accuracy. They are not affected by environmental conditions, but are cumbersome and intrusive to most simulation tasks because of the physical connection and limited motion range. Examples of mechanical tracking systems range from the device used by Sutherland for a prototype head mounted display tracker (Sutherland, 1968) to Fake Space Lab's BOOM display system. Mechanical tracking systems are not considered useful for small arms weapon fire simulation due to the restraints placed on movement of the weapon.

Inertial

Inertial based trackers use three orthogonal solid-state acceleration sensors along with solid-state gyros, magnetic compasses, and inclinometers for determining position and orientation changes. These tracking systems are termed sourceless because they do not use emitters, but rely on changes in inertia to indicate movement. Accelerometer sensors are created via a process of micromachining, where the accelerometer structure is etched out of silicon by the same process used in making integrated circuits. Each axis of the 3-axis sensor contains two micromachined capacitive elements that respond to acceleration by changing their capacitance. Integrated circuits can be integral to the sensor package, allowing measurement of the capacitance and conversion into a digital output. The three axis accelerometer system provides only relative 3D position. The outputs of the sensor are integrated once to determine instantaneous velocity values and a second time to obtain instantaneous position. The addition of gyros provide angular rates for yaw, pitch, and roll changes. Orientation changes are found by integrating the gyro outputs, with one method periodically resetting the orientation by use of the magnetic compass (for yaw) and inclinometers (for pitch and roll).

A big advantage of inertial trackers is that they are sourceless and can be arranged to work in a tetherless manner allowing for an almost unlimited motion box with unlimited orientation angles. Update rates can be up to 500 Hertz and can allow for motion prediction which can be used to reduce throughput lag. Angular resolution is 0.02 degrees RMS, while angular static and dynamic accuracies are 3 degrees and 1 degrees, respectively. Angular jitter without filtering and loss of tracking sensitivity with filtering are primary disadvantage of inertial trackers in weapons tracking tasks. Another disadvantage is the lack of position data, which can be added through hybrid technologies (e.g., inertial and acoustic). The additional technology brings its limitations and the integration of the hybrid technologies causes new problems

Magnetic

The basic magnetic tracking system consists of a Magnetic Transmitter and a Magnetic Receiver (or sensor), along with a system control unit. The Magnetic Transmitter generates three separate electromagnetic fields from three orthogonal coils. Three orthogonal coils in the tracked sensor react to the electromagnetic fields by having a voltage induced in them proportional to the distance and orientation from the emitter. From these voltages, the orientation (roll, pitch, yaw) and the position (x, y, z) are calculated.

Systems employing magnetic sensors normally have software filtering to remove noise picked up by the sensors. This filtering has the effect of increasing accuracy and lag. The resolution and accuracy of magnetic tracker position and orientation data is dependent on the transmitter to sensor separation. The best translation resolution claimed is 0.0002 inches per inch of transmitter to sensor separation. Some systems only provide a single accuracy specification such as numbers like 0.03 inch (0.76 mm.) in translation and 0.15 degree in orientation. Other specifications may list the accuracy within area blocks, such as: a translational accuracy of 0.03 inch RMS and orientation accuracy of 0.5 degrees RMS for up to 5 feet of sensor separation from the transmitter, dropping to 0.6 inch RMS and 1.0 degrees RMS at 10 feet separation.

The magnetic fields employed in magnetic tracking systems can be either AC or DC. AC refers to a pulsed magnetic field, while DC refers to a steady state magnetic field (during sampling). The AC type is more sensitive to interference from metals in the motion range. Eddy currents are produced in metals by the changing magnetic field resulting in localized magnetic fields. These localized fields sum with the transmitter's magnetic field and cause distortion and loss of accuracy. The DC magnetic field is claimed to be less affected by interference caused by metal objects. The DC systems perform measurements when the magnetic field is static, after the eddy currents produced at the start of the measurement have decayed. However, the DC type is sensitive to the earth's magnetic field, and requires a technique of subtracting the earth's magnetic field for each measurement. DC systems are still affected by metals as they reflect the magnetic field and cause measurement errors.

Advantages of Magnetic Trackers include: no line of sight restrictions, update rates to 120 Hertz, full 6DOF with unlimited orientation angles (±180° in yaw and roll, ±90° in pitch), and some systems can be upgraded to track 30 to 120 sensors. One of the disadvantages is sensitivity to background magnetic fields and metal in the vicinity. Care must be taken to keep metal out of the operating range, with particular problems occurring with metal in floors (concrete) and walls, and with metal furniture. Wood and other nonmetal materials must be used for mounting the transmitter (in general metal should be kept 8 feet from the sensors). For weapons tracking, this distance requirement cannot be met, because weapons (demilled) used in simulations contain metal parts. CRT based displays will develop image jitter when near the magnetic transmitters and can cause measurement errors. The sensor targets are usually connected to the system control unit by cables, which restrict motion and are subject to damage (however some systems are starting to use wireless communication between the targets and the control unit).

Radio Frequency (RF)

RF devices are being investigated for use in 3DOF/6DOF tracking systems by creating a "mini" GPS system. RF systems are used in an Outside-In arrangement to provide position and/or orientation. Still in a research and development phase, these trackers promise a large tracking range (>50m) and high update rate (1kHz), while providing 2 mm position accuracy, 1 degree angular accuracy, tetherless operation, multiple users, and no problems with interference or LOS.

WEAPONS FIRE SIMULATION TRACKING ISSUES

Weapons fire simulation for small arms presents unique and demanding requirements on the application of weapon tracking systems. In this report, small arms refer to weapons that are generally handheld (e.g., rifles). In general, trainees engage simulated threats or targets with a simulated weapon from within a synthetic environment. The simulated threats are typically imaged on a large screen display. As a minimum, the weapon tracking system must provide the 2D weapon aimpoint to the system computer relative to the display screen coordinate system. From the 2D weapon aimpoint, measures of weapon position and orientation can be determined, providing a complete weapon attribute set for weapon fire simulation. Alternately, 3D weapon tracking systems can provide weapon position and orientation directly, leading to the complete weapon attribute set. Using this complete attribute set, specified relative to the synthetic environment, a complete projectile flight solution is possible. Ballistic equations and environmental effects are modeled by the simulation computer to accurately fly a projectile to its terminal position.

The accuracy requirements for the set of tracked weapon attributes will change depending on the type of training. Generally, small arms training can fall into two categories: marksmanship training and tactics training. In marksmanship training, the weapon tracking system must exceed the accuracy of the weapon used to obtain accurate measures of performance variables. In a tactics training device, the accuracy requirements are not so clear, but are typically less demanding. In either case, an awareness is required of the accuracy of the weapon tracking system employed and how it relates to the overall training tasks. An important first step in determining weapon tracking simulation requirements is to understand the task of weapon fire simulation in terms of the characteristics of the weapon being simulated.

EXAMPLE REQUIREMENTS

As a quick example of the potential demands of weapon tracking, consider the basic requirements for finding the weapon aimpoint position when tracking the orientation of an M16 weapon. The weapon orientation is expressed in terms of μrad, or 1×10^{-6} radians. The M16A2 rifle is generally regarded to have a live fire angular dispersion error (round to round dispersion) of approximately 300 μrad @ one standard deviation (1SD) (Torre). Note that since the weapon error is represented as an angular error, the error at the target plane is a function of range. For example, given a 300 μrad angular error, a gunner shooting at a target 300 meters in range would expect to shoot no better than ± 0.045 meters. Table 1 lists the linear displacement errors for various target ranges given an angular dispersion error of 300 μrad and 1000 μrad. Table 1 clearly indicates that as the range to target increases, the linear displacement error at the target plane also increases; although the angular error has remained constant. Table 1 also shows the dramatic effect of a 1000 μrad angular tracking error in terms of tracking error at the target plane.

Table 1. Angular Dispersion / Linear Displacement Error as a Function of Range
(Angular error = 300 μrad and 1000 μrad)

Range	**Error (300 μrad)**	**Error (1000 μrad)**
100m	0.03 m	0.1m
200m	0.06m	0.2m
300m	0.09m	0.3m
400m	0.12m	0.4m
500m	0.15m	0.5m
600m	0.18m	0.6m

The requirements for both 3DOF and 6DOF weapon tracking systems can be specified directly in terms of angular error, since they both can ultimately provide a vector or orientation representation of weapon aim. Since the minimum acceptable error for the M16 weapon is approximately 300 μrad (1SD), we should specify a weapon tracking accuracy error of no more than 150 μrad. This will allow us to effectively eliminate the weapon tracking system from the sources of potential tracking errors. Therefore, a 3DOF or 6DOF weapon tracking system should have a maximum angular error of 150 μrad or 0.0086 degrees. Unfortunately, this is currently orders of magnitude smaller than any commercially available 3DOF or 6DOF weapon tracking systems.

In a 2DOF weapon tracking system, only the 2DOF aimpoint is tracked as it relates to the trainee's weapon aimpoint on a large screen display system. By providing the screen based aimpoint, 2DOF weapon tracking systems operate quite differently than their 3DOF or 6DOF counterparts. In this case, we need to convert the aimpoint angular error requirement to an equivalent linear displacement error on the display screen. The conversion from the angular error to a linear displacement error is based on how far the trainee is from the display screen. The distance from the trainee's eyepoint to the display screen in conjunction with the angular error requirement determines the linear displacement error at the display screen surface. If we assume a typical viewing distance of 180 inches (15 feet), a 150 μrad dispersion error represents a total linear displacement error, d_e, of:

$$d_e = \tan(150\ \mu\text{rad}) * 180 \text{ inches} = 0.027 \text{ inches.}$$

For this situation, a 2DOF tracking system would need to provide screen coordinates within a maximum error of 0.027 inches (0.69 mm) to meet the 150 μrad requirement.

The sample weapon tracking requirements shown above indicate the demanding requirements placed on weapon tracking systems for small arms simulation. Currently, only 2DOF weapon tracking systems approach the necessary accuracy for marksmanship simulation. As advances in 3DOF and 6DOF tracking technologies continue, they are becoming candidates for weapons tracking. However, as these 3DOF and 6DOF tracking systems were evaluated for weapons fire simulation, it became evident that a standardized method for testing was needed for all tracking systems to verify their performance.

TEST TRACK EQUIPMENT

DESCRIPTION OF TRACKING TEST EQUIPMENT

Test equipment was setup to provide accurate and precise target movement for the static and dynamic accuracy measurements. The tracking test equipment includes a servo-controlled linear motion track with controller hardware operated via a Pentium PC computer. The computer contains specific motion track control software, a motion track interface card, and a timer card. An interchangeable part of the testing setup is the tracking system under test, its interface, and any necessary software library routines. A diagram of the tracking test equipment is shown in Figure 5, with an ultrasonic tracker depicted for example purposes.

Software for the control computer, the AWST Tracker Test program, was written to control both the linear motion track and the tracking systems being tested. This Windows 95 based tracker test software performs various preprogrammed movements of the track after initiating the tracking system to track the target. After target data is captured, the AWST tracker test program executes statistical calculations on the data to measure the tracking system's performance. The preprogrammed tests performed are described in the Tracking Test Procedures section. The tracker test software is discussed in appendix A.

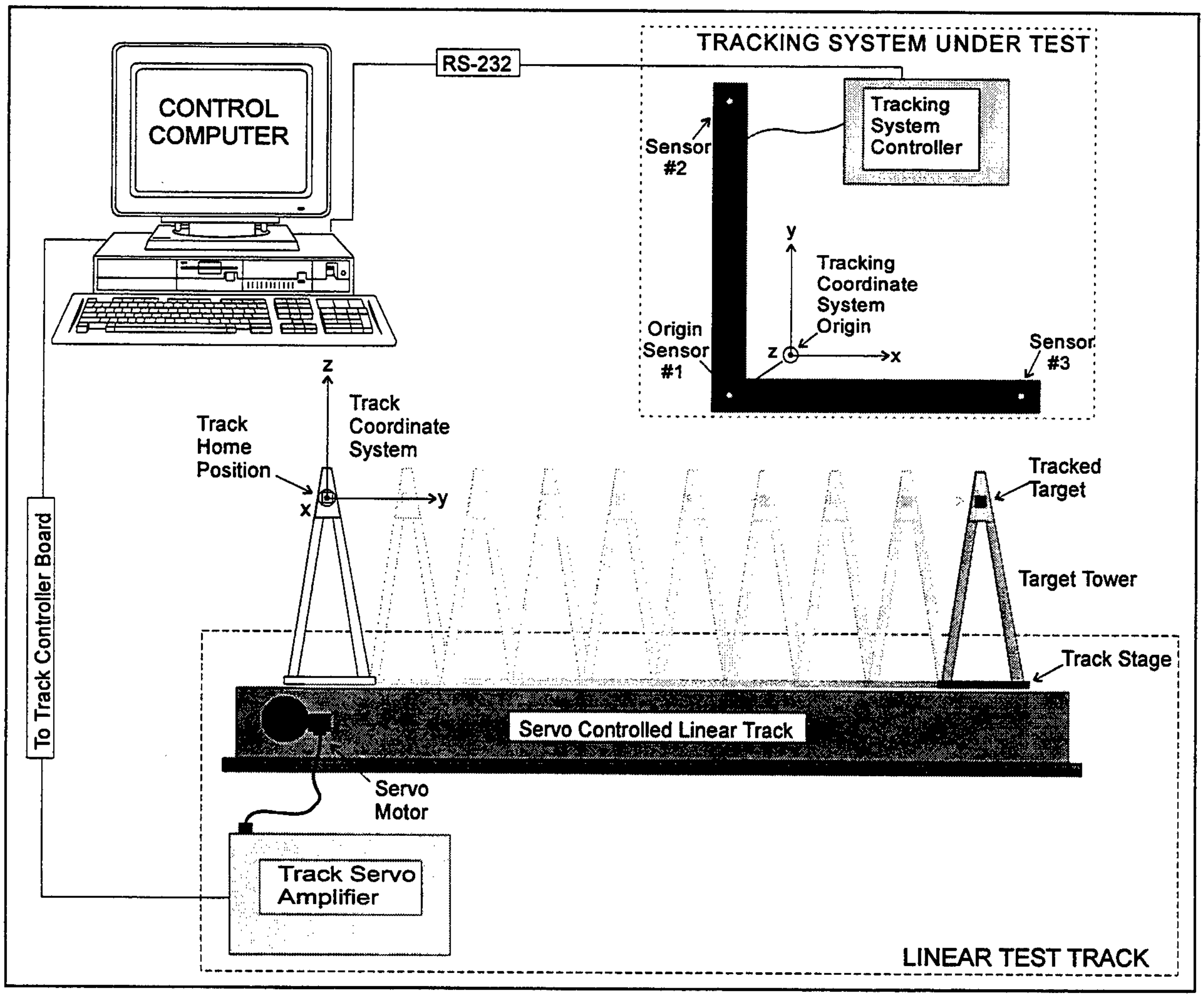

Figure 5. Tracking System Test Equipment.

The linear motion track used is a product of Aerotech, Incorporated. The system is a combination of the UNIDEX (U500) PC ISA bus motion control card, windows interface software, and a linear translation stage controlled by an optically encoded motor. The linear motion stage is an Aerotech model ATS70120-U-TB, and the motor is an Aerotech model 1135LT-MSOF/E1000LD. Throughout this report, we refer to the entire system as the U500.

The U500 system allows for high resolution linear motion of the track stage along its length of 1200 millimeters (mm). The optical encoder, with 4,000 steps/revolution, monitors motor revolutions to determine the position of the track stage that is attached to the motor via a belt drive. For maximum accuracy during testing, all track position data is obtained in a unidirectional manner to eliminate mechanical backlash. This unidirectional motion starts at a predefined "Home" position, which, referring to Figure 5, defines the origin of the track 3D coordinate system. The track coordinate system is defined to indicate track movement by changes in the y axis coordinate.

The track can be programmed to go to positions with a precision of 0.001 mm in Metric mode or 0.0001 inches in English mode. However, the actual positioning is limited to increments of 0.025 mm and 0.00098425 inches. These actual positioning values are referred to as the *machine resolutions* by the manufacturer, and may also be interpreted to be the track positioning precision. When instructed to move to a position that is not an integer multiple of the machine resolution, the U500 will move to the nearest machine resolution position. Regardless, the reported position of the track stage is the actual machine resolution position as determined through the servo-controller and optical encoder. The U500 system provides point-to-point motion, absolute and incremental positioning, constant velocity motion, velocity profiled motions, time based motions, free run motions, and electronic gearing by ratio. As configured by the manufacturer, the maximum velocity of the translation stage is 750 mm/second. We have limited the maximum velocity to 600 mm/sec due to an increase in mechanical and acoustic noise from the system that might affect acoustic/ultrasonic trackers.

The timer card used is a National Instruments timer card, model PC-TIO-10. This card uses digital counters and a crystal oscillator with a frequency of 5MHz to provide 200 nanoseconds (nsec) timing resolution.

VERIFICATION OF THE TEST TRACK

The ability of the track system to move to commanded positions was tested to verify the test track encoder output. Our primary goal in testing the track was to ensure that the track had better resolution and accuracy than the best available tracking systems and the most stringent requirements of weapons simulation tracking. Within this goal of testing the track, we wanted to verify that the track stage could be positioned within the manufacturer's relative accuracy of 20 microns (μm)/25mm (0.0008 inches/inch).

Cumulative error values for the track length of 1050 mm were taken in 25 mm increments. The measurements of table position were obtained using a Mitutoyo UDR-220 linear gauge with a certified maximum error of 0.00025 inches over 40 inches. The UDR-220 measured position of the track stage was compared to the track position reported via the servo controlled motor and hardware/software interface. The cumulative errors were then compared to the Unidex specification of 20 μm/25.4 mm (0.0008 inches/inch).

Figure 6 shows the cumulative position errors relative to the reported position along the track length. The Unidex error specification of ±20 μm/25mm (±0.0008 inches/inch) is depicted on the error chart, with the area between the + and – specification lines indicating error values that are within the specification. From the figure, the cumulative error values are positioned just below the zero error line well within the boundary of the Unidex specification except within the first 50 mm. The error values never exceed 0.129 mm from the desired position. The mean cumulative error over the 1050 mm (41.34 inches) of stage travel is -0.0546 mm (0.0020 inches), with a standard deviation of 0.007 mm (0.00027 inches). Negative error values indicate that the reported position is less than the measured position. Figure 6 indicates that the reported position of the U500 stage tends to be less than its actual position. As a reference point, the errors shown in the chart have a peak value of -0.129 mm (0.005 inch) at a stage position of 750.0 mm (29.5 inches) and an error of -0.037 mm (0.001 inch) at the 500.0 mm (19.68 inch) position. For the 1050 mm travel range measured, the track accuracy specification states that the maximum error should be limited to 840 μm or 0.84 mm (0.033 inches). The cumulative error at 1050 mm (41.34 inches) was measured as -0.127 mm (-0.005 inches), well within specification.

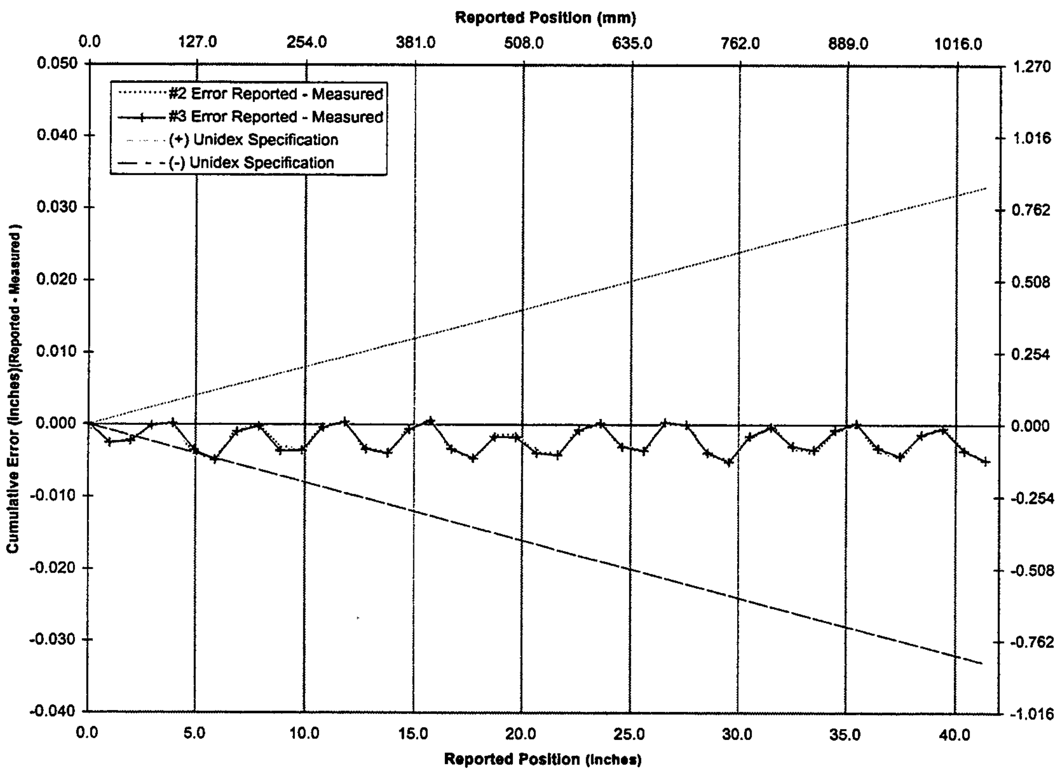

Figure 6. UNIDEX 500 Track Cumulative Error.

In summary, the U500 track performs within its published specification, with a maximum error of -0.129 mm and an accuracy of -0.0546 mm ± 0.0459 mm (@1SD). The U500 is capable of measuring tracking systems with accuracies that approach 0.1 mm. Referring to the previous weapon tracking example requirements for the M16A2, the U500 is more than capable of measuring within the 0.69 mm accuracy required.

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TRACKING TEST METHODS

GENERAL TRACKING TESTS DISCUSSION

Use of the U500 track as a high resolution motorized linear positioner allows testing of various parameters of a tracking system. With allowed track movement only in a one dimensional direction, a majority of the tests involve testing specifications that deal with 3D positioning relative to linear motion. The U500 optical-encoder output provides the position of a tracking target along the track relative to the track home position. In addition to the linear positioning tests, some testing is performed of the roll, pitch, and yaw angle variations (associated with 6DOF trackers).

Tracking System Tests and Noise Filtering. When performing the resolution data collection, the topic of noise filtering should be addressed. Noise filtering can have a significant effect on the sample time and position resolution since most methods involve averaging over time. Since implementation of noise filtering is not under user control, resolution data collection should be performed without noise filtering. For cases where noise filtering can not be turned off, use of filtering should be noted.

The Relationship Between Precision, Resolution, and Accuracy. The relationship between the terms of precision, resolution, and accuracy for measurement devices such as tracking systems is complex. In general, accuracy is less than the resolution specification and resolution is less than precision. There may be a few cases where accuracy, resolution, and precision are equal, but there can not be any cases where accuracy is greater than resolution or precision, or where resolution is greater than precision. See the Tracking System Terminology section for definitions of these terms.

Static vs. Dynamic Accuracy

When tracking weapons, there are two distinct tracking situations of interest: a static case (marksmanship), where the weapon is barely moving (or not at all); and a dynamic case, where the weapon is moving at moderate to high angular and translational rates. Tracking systems can have entirely different accuracies for the static and dynamic cases, leading to entirely different results in a weapons firing simulation. The difference between these two movement situations is related to whether the tracked target moves during the sample period.

The U500 system has the ability to provide the required position information while either stationary or moving. Tests were designed for both the static and dynamic situations. The difference between these tracker tests is that the static case averages multiple tracker samples for a single position of the tracked target, while during the dynamic testing there is no averaging. During the dynamic tests only one tracker sample is taken at each position. The static accuracy test is performed at incremental positions along the track by taking multiple tracker samples with the track stage stationary. The dynamic accuracy test is performed by taking tracker samples continuously during track stage motion. Thus, the static accuracy tests have the advantage of increased accuracy values due to averaging, while the dynamic accuracy tests involving single samples will have the effects of the tracker system noise and movement artifacts on top of the measurement data.

Importance of Dynamic versus Static Tests. The dynamic tests described in the Tracking Test Procedures section examine a tracker's performance under conditions that are similar to those encountered during actual weapons fire simulation use. These conditions involve tracking a target attached to a moving object (e.g., a weapon), sampling and calculating the target position/orientation during target movement, and transferring the target position and orientation data to a host computer. The key difference in dynamic tracking is that target movement does not allow for averaging of tracking data to improve the resolution or accuracy. During a dynamic movement, the position and orientation values are unique in time, and averaging would smear those values. The effect would be to reduce tracking resolution and accuracy. Even in the static marksmanship case, averaging over more than a few samples is of little practical use.

In the dynamic tests, what really matters is how the tracking system performs on a sample by sample basis where single data outputs are used without any averaging. To properly analyze the dynamic data, it is important to collect every data value from the tracking system. Equally important is to collect the data at a rate that is comparable to rates used in actual simulation exercises. To ensure the data collection efficiency, the tracker to host interface type, protocol, and data transfer format need to be considered.

Tracker Interface Considerations. There are two types of hardware interfaces generally used between a tracking system and the host computer: RS-232C (serial) and Ethernet. Other possibilities exist (e.g., parallel or proprietary interfaces), but serial and Ethernet are common, with serial the most prevalent. Most newer computers already have serial ports that are fast enough for tracker data transfer. If an Ethernet option is available, its use can provide for faster tracker data transfer that may reduce throughput lag.

Regardless of the interface used, the transfer of tracking data will probably use one of four methods of handling the transfer of tracking data: polled, continuous, interrupt, and synchronous.

In the polled method, the host computer (through various timing schemes) sends a signal to the tracker to request a data sample. The tracking system responds by initiating a sampling of the target, calculates the target data set, and then sends the data to the host. A variation of the polled method has the tracker continuously updating the target data in its own buffer, but only sending the data to the host upon request.

In the continuous method, the tracking system is set to continuously sample the target, perform the target calculations, and send the data to the host. The host computer must be ready to accept the data, either through hardware handshaking and/or by software handshaking.

The interrupt method also has continuous tracking occurring, with the tracking system signaling the host via an interrupt signal when the data is ready. The data transfer occurs via interrupt handling, with all other host tasks suspended.

In the synchronous method, an external synchronization signal such as a video vertical sync signal is used to start a tracking system's target sampling. This same synchronization signal is also used, with a time delay added, to interrupt the host computer to accept the tracking data.

Effects of Using Different Interface Protocols. Where timing is not important, (i.e., for a static target), the manually polled method is the simplest method to implement. A disadvantage of manual polling is that the target sampling time is added to the data lag. The continuous/polled method is more appropriate for moving targets, where the most recently gathered target data is sent to the host. For the continuous/polled protocol, the data can be sent immediately with lag primarily due to the data transfer time. The continuous method also provides the data immediately. Using hardware handshaking between the tracker and host allows the transfer of data to a hardware buffer without the host CPU intervention. However, as the hardware buffer fills, the CPU will be interrupted to keep the buffers from overflowing. This allows the host to be performing other tasks and to read the tracker data out of the buffer when necessary. Using software handshaking requires the host CPU to become involved in the data transfer, implying that the host must be finished with other tasks and ready to accept the data. If neither hardware or software is ready, the data set is lost, and the simulation positioning and timeline will be out of synchronization. The synchronous method is used to guarantee that the data will always be ready at the same time within the processing cycle. However, setting up the synchronous method requires a careful coordination of timing for all hardware and software elements of the simulation.

Transfer Data Format. Another consideration during data transfers is the data format. Two common formats are ASCII and binary. In the ASCII format, data is sent as a series of characters as defined by the ASCII standard, one byte per character. Each value sent, such as the x position value, is composed of the alphanumeric characters that make up the data value. The ASCII format is generally easier to implement, but has a timing drawback due to the number of bytes required to provide each data value. As an example, the data format could include seven bytes: a sign byte, 3 digits, a decimal point, and 2 more digits. For example: +100.95. At the start of a data set there may be a header character and a count value for the number of characters (bytes) to follow. There is usually a delimiter (e.g., a space character) to separate the data values and another delimiter (e.g., carriage return and linefeed characters) to mark the end of the entire data set. In this example, each complete tracker data set of (x, y, z, yaw, pitch, roll) would require 60 bytes. Even at 115,200 baud (bits/sec), with each byte taking 10 bits (1 start bit, 8 data bits, and 1 stop bit), transfer of 60 bytes amounts to 5.2 msec. In the continuous mode with hardware handshaking, this transfer time can occur outside the host's critical time path and not affect the data cycle. In other methods, this transfer time becomes part of the data cycle and would affect the tracker lag.

The binary format can provide the tracker data as floating point values, possibly in 4 bytes (IEEE 32bit float values) per data value. Including a 4 byte data header, the byte count for tracker data in binary format would drop to 32 bytes. The binary format is a little more difficult to implement, but allows for faster data transfer.

Not all tracking systems support all of these interface types, protocols, and formats. The two most common interfaces are the serial followed by Ethernet. The preferred method for high speed data transfer is the continuous method with hardware handshaking. Whatever setup is to be used, it is important that the tracker have a method of interface that will allow the tracking data set to be transferred at rates that are appropriate for the tracking and simulation task at hand. This would involve a data update rate that matches the frame rate of the simulation display (e.g., 60 Hertz). Faster update rates from some trackers may be possible, and may be used in various schemes for removing tracker lag effects. However, the important consideration for dynamic tracking is that the tracking data samples should have minimal lag, while the host and interface configuration should not allow data samples to be missed.

Track and Tracker Alignment

There are two alignment procedures performed before the static and dynamic accuracy tests are initiated: a physical track alignment and a mathematical coordinate system alignment. The first alignment is a physical positioning of the U500 track relative to the coordinate system of the tracking system being tested. There are two reasons for the physical alignment: 1) to place the U500 track at particular positions within the tracker motion volume, and 2) to orient the axis of the track to have a particular alignment relative to the axes of the tracker coordinate system. Knowledge of the track position allows data to be taken at various positions within the specified tracker motion volume to look for distance related effects. Setting the orientation of the track axis allows data to be taken for a target motion path at a fixed angle relative to the tracker coordinate system axes to look for directional dependencies. This physical alignment is intended for 3DOF and 6DOF tracking systems which provide 3D coordinates.

The physical alignment of the track uses the 3D position of the tracking system target in the tracker's default 3D coordinate system. The physical alignment is facilitated in the software by providing a display of the target's 3D coordinates and a method for quick repositioning of the track stage from the "Home" to endpoint positions. The physical alignment is performed by positioning the target at the U500 "Home" position and noting the 3D position, followed by moving the target to the endpoint of the track and noting the endpoint 3D position. To orient the track parallel to the tracker's x-axis, for example, the changes in the target's 3D coordinates should only be in the x coordinate. A track orientation of 45 degrees to the tracking system's positive x and y axes would have equal changes in the x and y coordinates between the "Home" and endpoint positions. After the "Home" and endpoint positions have been examined for the alignment desired, the track can be physically moved to improve the track alignment and the physical alignment data is then gathered again to verify the alignment.

The second alignment is a mathematical transformation of the 3D coordinates output by the tracking system. The transformation is to a new coordinate system with an origin located at the U500 "Home" position and a y-axis aligned to the U500 linear motion axis. The purpose of this mathematical alignment is to force the 3D coordinates of the target motion to be along the linear track and relative to the U500 "Home" position. After this alignment, the target position changes should be seen only in the y coordinate. The tracker test software includes these two alignments, with provisions to perform them separately.

The mathematical alignment is generally performed after the physical alignment. The mathematical alignment is performed by averaging 100 3D position samples taken at the track "Home" and endpoint positions. These averaged positions are used to define the track axis vector in the tracker coordinate system. The "Home" 3D coordinate is used to translate the base of the track vector to an origin coinciding with the U500 track "Home" position. Angles are then calculated for rotating this track vector onto the y-axis of the U500 coordinate system. The translation values and the rotation angles are then stored for later use in transforming 3D position data from the tracker coordinate system to the U500 track coordinate system.

TRACKING TEST PROCEDURES

This section contains descriptions of proposed standardized test procedures to evaluate the performance of tracking systems. Discussions include the procedures involved for each test, the data to be collected, and the calculations to be performed. These procedures, data collection, and calculation tasks have been integrated into the tracker test program (discussed in Appendix A). The test procedures and data analyses implemented in the test program are:

Resolution

- Position and Orientation Resolution
- Mean Position and Orientation Resolution
- Resolution versus Servo Track Operation

Static Accuracy

- Static Position Accuracy Analysis
- Static Position Error Plot
- Static Orientation Stability Analysis
- Static Orientation Stability Plot

Dynamic Accuracy

- Dynamic Position Accuracy Analysis
- Dynamic Position Error Plot
- Dynamic Lag Analysis
- Dynamic Position Error and Lag Plot
- Dynamic Orientation Stability Analysis
- Dynamic Orientation Stability Plot

The goal of the tests described in this section is to acquire data that will yield a set of characteristics indicating the performance of the tracking system being tested. For each tracking system, a software interface module must be defined to allow for tracking system functions such as: reset, initialization, set tracking modes (e.g., coordinate system, # of DOF, get data continuous or single point, wake-up, sleep). Interface routines have been written for several available tracking systems, and can be used as examples for integrating and testing new tracking systems. Once these interface routines have been written, the tracker test program will handle the track motions required, collect the data, and perform the statistics. Graphic plots are done by importing the program data output files into an Excel spreadsheet. Appendix C contains sample outputs that are results of the test program and Excel procedures.

Resolution

For the resolution characteristics the following are analyzed:

- Position and Orientation Resolution
- Mean Position and Orientation Resolution
- Resolution versus Servo Track Operation

Resolution values are calculated by statistical methods. For purposes of this report on tracking systems, resolution is defined as one standard deviation from the mean of 100 tracker data records. These 100 data records are taken with the tracked target held stationary. The target is attached to a rigid stand and then positioned within the tracking system motion volume. Resolution values for the system are quoted with the servo system in a powered off mode to remove any possible interference effects. The proposed method takes sets of 100 data values at three positions within the motion volume. These positions should be near the center of the tracking system motion volume and along (or parallel to) the major axis of the tracker's coordinate system. Ideally, two of the positions will be at approximately 50% and 100% of the tracker's specified range. These positions will indicate the tracker's performance versus its specifications. The third position should be at a range of 1 meter allowing for direct comparisons at a common tracking range between individual tracking systems.

The data value contents of each record depends on the Degrees Of Freedom (DOF) of the tracker. For a 2DOF tracker the record would contain only (x, y) position data values. 3DOF trackers have an additional position data value and provide (x, y, z) in the record. A full 6DOF tracker would add yaw, pitch, and roll angles to the (x, y, z) position.

Position and Orientation Resolution. To measure position resolution, the tracker target is mounted on a stand and 100 data records are recorded by the tracker test program. Using the position data values from the 100 samples, the equations of Table 2 are used for calculating the position arithmetic means and position resolutions for each coordinate axis. From the independent position resolutions for each axis, the radial resolution, σ_R, is calculated. The σ_R value defines the radius of a spherical resolution cell centered on the mean 3D target position as depicted in Figure 7, or the radius of a circular cell centered on the mean 2D position for 2DOF trackers. This sphere, or circle, has a 68% probability of containing any of the 100 position samples. Restated, any position sample outside this sphere of radius σ_R is considered to be statistically different from the

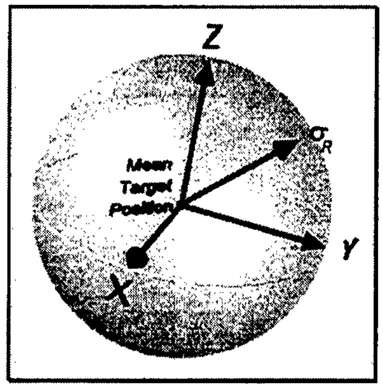

Figure 7. Spherical Resolution Cell.

Table 2. Position Resolution Statistics

POSITION ARITHMETIC MEANS

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, \quad \text{where } X_i \text{ are the } n \text{ measured values of X}$$

$$\overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i, \quad \text{where } Y_i \text{ are the } n \text{ measured values of Y}$$

$$\overline{Z} = \frac{1}{n}\sum_{i=1}^{n} Z_i, \quad \text{where } Z_i \text{ are the } n \text{ measured values of Z}$$

POSITION RESOLUTIONS

$$\sigma_X = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{iX}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{iX} = \left(X_i - \overline{X}\right)$$

$$\sigma_Y = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{iY}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{iY} = \left(Y_i - \overline{Y}\right)$$

$$\sigma_Z = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{iZ}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{iZ} = \left(Z_i - \overline{Z}\right)$$

RADIAL RESOLUTION

$$\sigma_R = \left(\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2\right)^{\frac{1}{2}} \text{ (3D), or } \sigma_R = \left(\sigma_X^2 + \sigma_Y^2\right)^{\frac{1}{2}} \text{ (2D)}$$

mean value and indicates that the tracker has indicated that the target is not at the mean position. When operating the tracking system, any tracker data output with a distance from one position to another that exceeds the position radial resolution indicates that the target has moved. Thus, the target movement has been resolved.

For 6DOF tracking systems there are the additional data values of roll, pitch and yaw to consider. Again, statistical procedures are used to find the mean of each of the roll, pitch and yaw values of the 100 records. This is followed by a calculation of the orientation resolutions for the individual angles of yaw, pitch, and roll (σ_{YAW}, σ_{PITCH}, and σ_{ROLL}). Combination of the orientation resolutions (similar to the position radial resolution) is only done for the yaw and pitch angles. The roll angle does not affect the direction of the orientation vector. This combination of the yaw and pitch resolutions produces a conic resolution value, σ_C, that can be visualized as the half angle of a cone about the vector representing the mean yaw and pitch orientation (see Figure 8). The half angle, σ_C , of this conic resolution represents a minimum change in the tracker yaw and pitch orientation outputs that indicate that the orientation vector has actually been repositioned in yaw and pitch. The σ_{ROLL} resolution value represents the minimum change about the mean yaw and pitch vector that indicates an actual roll angle modification. The equations for calculating the orientation resolutions are shown in Table 3.

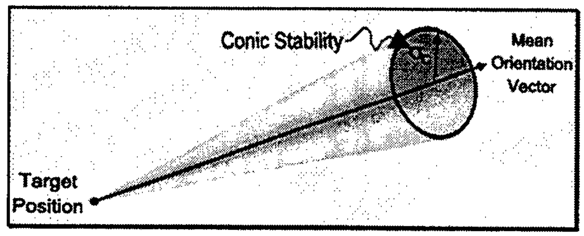

Figure 8. Conic Stability Cone.

Table 3. Orientation Resolution Statistics

ORIENTATION ARITHMETIC MEANS

$$\overline{Yaw} = \frac{1}{n}\sum_{i=1}^{n} Yaw_i, \quad \text{where } Yaw_i \text{ are the } n \text{ measured values of } Yaw$$

$$\overline{Pitch} = \frac{1}{n}\sum_{i=1}^{n} Pitch_i, \quad \text{where } Pitch_i \text{ are the } n \text{ measured values of } Pitch$$

$$\overline{Roll} = \frac{1}{n}\sum_{i=1}^{n} Roll_i, \quad \text{where } Roll_i \text{ are the } n \text{ measured values of } Roll$$

ORIENTATION RESOLUTIONS

$$\sigma_{Yaw} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{iYaw}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{iYaw} = (Yaw_i - \overline{Yaw})$$

$$\sigma_{Pitch} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{iPitch}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{iPitch} = (Pitch_i - \overline{Pitch})$$

$$\sigma_{Roll} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{iRoll}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{iRoll} = (Roll_i - \overline{Roll})$$

CONIC RESOLUTION

$$\sigma_C = \left(\sigma_{Yaw}^2 + \sigma_{Pitch}^2\right)^{\frac{1}{2}}$$

To summarize the results of the resolution measurements and calculations, the position resolutions of Table 2 and the orientation resolutions of Table 3 relate the resolution ability of the tracker being tested in terms of the standard deviation of 100 data record values from their means. The values of σ_X, σ_Y and σ_Z are the individual resolution values for the x, y, and z axes of the tracker, with σ_R providing a measure of the overall position resolution. Similarly, the σ_{YAW}, σ_{PITCH}, and σ_{ROLL} are the individual resolution values for angular measures about the three axes of the tracking coordinate system, with σ_C providing a measure of the resolution of the pointing direction of a vector defined by the yaw and pitch angles.

Mean Position and Orientation Resolution Tests. In evaluating the results of the position and orientation resolution tests, some tracking system outputs have exhibited random noise that causes the position and orientation standard deviations to vary widely. For these cases, a number of resolution sample sets of 100 records should be taken to check for variations in the position resolutions. A suggested number is 10 data sets. This would give 10 corresponding statistical output sets of: mean positions, position resolutions, radial position resolution, mean orientation angles, orientation angle resolutions, and conic resolution. These are the values calculated via the equations of Table 2 and 3.

These position resolution means and resolution sets can then be statistically analyzed to find the average position arithmetic means, average position resolution, and the corresponding position resolution standard deviations. Ideally, the standard deviation of this set of position resolution means should approach zero, indicating that there is little change between the statistics of each 100 data sample set. The position resolutions of the tracking system are then defined to be the mean of the average position resolution plus one standard deviation of the position resolution. The average radial resolution plus or minus one standard deviation provides the most condensed position resolution value for a tracking system with position output.

In the same manner, the values of orientation angle means and angular resolutions (independent yaw, pitch, roll, and conic) are then statistically analyzed to find their means and standard deviations. The orientation resolutions of the tracking system are then defined to be the mean of each orientation resolution plus their corresponding standard deviation. The mean conic resolution plus or minus one standard deviation, together with the mean roll resolution plus or minus one standard deviation provides the most condensed orientation resolution values for a tracker with orientation output. The equations for evaluating the mean position and orientation statistics are given in Table 4 and 5.

Note that there are some cases where either the position or orientation standard deviations will be zero, indicating that the tracking system output did not change for the duration of the test. This lack of change may be related to filtering that can not be disabled. For this case, the resolution of the system can not be measured by using a stationary target. For this case, the target would need to be moved until the output data values indicated a change in position or orientation. This change could be interpreted, with caution, as the resolution.

Table 4. Mean Position Resolution Statistics

AVERAGE POSITION ARITHMETIC MEANS

$\overline{\overline{X}} = \frac{1}{n}\sum_{i=1}^{n} \overline{X}_i$, where $\overline{X}_i$ are the n calculated means of X

$\overline{\overline{Y}} = \frac{1}{n}\sum_{i=1}^{n} \overline{Y}_i$, where $\overline{Y}_i$ are the n calculated means of Y

$\overline{\overline{Z}} = \frac{1}{n}\sum_{i=1}^{n} \overline{Z}_i$, where $\overline{Z}_i$ are the n calculated means of Z

AVERAGE POSITION RESOLUTIONS

$\overline{\sigma}_X = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Xi}$, σ_{Xi} are the n calculated resolutions of X

$\overline{\sigma}_Y = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Yi}$, σ_{Yi} are the n calculated resolutions of Y

$\overline{\sigma}_Z = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Zi}$, σ_{Zi} are the n calculated resolutions of Z

$\overline{\sigma}_R = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Ri}$, σ_{Ri} are the n calculated radial resolutions

STANDARD DEVIATION OF MEAN POSITIONS

$$\sigma_{\overline{X}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{X}}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{X}} = \left(\overline{X}_i - \overline{\overline{X}}\right)$$

$$\sigma_{\overline{Y}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{Y}}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{Y}} = \left(\overline{Y}_i - \overline{\overline{Y}}\right)$$

$$\sigma_{\overline{Z}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{Z}}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{Z}} = \left(\overline{Z}_i - \overline{\overline{Z}}\right)$$

STANDARD DEVIATION OF POSITION RESOLUTIONS

$$\sigma_{\overline{\sigma}_X} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{\sigma}_X}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{\sigma}_X} = \left(\sigma_{X_i} - \overline{\sigma}_X\right)$$

$$\sigma_{\overline{\sigma}_Y} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{\sigma}_Y}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{\sigma}_Y} = \left(\sigma_{Y_i} - \overline{\sigma}_Y\right)$$

$$\sigma_{\overline{\sigma}_Z} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{\sigma}_Z}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{\sigma}_Z} = \left(\sigma_{Z_i} - \overline{\sigma}_Z\right)$$

$$\sigma_{\overline{\sigma}_R} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e^2_{i\overline{\sigma}_R}\right]^{\frac{1}{2}}, \quad where\ e_{i\overline{\sigma}_R} = \left(\sigma_{R_i} - \overline{\sigma}_R\right)$$

Table 5. Mean Orientation Resolution Statistics

AVERAGE ORIENTATION ARITHMETIC MEANS

$$\overline{\overline{Yaw}} = \frac{1}{n}\sum_{i=1}^{n} \overline{Yaw}_i, \quad \text{where } \overline{Yaw}_i \text{ are the } n \text{ calculated means of } Yaw$$

$$\overline{\overline{Pitch}} = \frac{1}{n}\sum_{i=1}^{n} \overline{Pitch}_i, \quad \text{where } \overline{Pitch}_i \text{ are the } n \text{ calculated means of } Pitch$$

$$\overline{\overline{Roll}} = \frac{1}{n}\sum_{i=1}^{n} \overline{Roll}_i, \quad \text{where } \overline{Roll}_i \text{ are the } n \text{ calculated means of } Roll$$

AVERAGE ORIENTATION RESOLUTIONS

$$\overline{\sigma}_{Yaw} = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Yaw_i}, \quad \sigma_{Yaw_i} \text{ are the n calculated resolutions of Yaw}$$

$$\overline{\sigma}_{Pitch} = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Pitch_i}, \quad \sigma_{Pitch_i} \text{ are the n calculated resolutions of Pitch}$$

$$\overline{\sigma}_{Roll} = \frac{1}{n}\sum_{i=1}^{n} \sigma_{Roll_i}, \quad \sigma_{Roll_i} \text{ are the n calculated resolutions of Roll}$$

$$\overline{\sigma}_{C} = \frac{1}{n}\sum_{i=1}^{n} \sigma_{C_i}, \quad \sigma_{C_i} \text{ are the n calculated conic resolutions}$$

STANDARD DEVIATION OF MEAN ORIENTATIONS

$$\sigma_{\overline{Yaw}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{Yaw}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{Yaw}} = \left(\overline{Yaw}_i - \overline{\overline{Yaw}}\right)$$

$$\sigma_{\overline{Pitch}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{Pitch}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{Pitch}} = \left(\overline{Pitch}_i - \overline{\overline{Pitch}}\right)$$

$$\sigma_{\overline{Roll}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{Roll}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{Roll}} = \left(\overline{Roll}_i - \overline{\overline{Roll}}\right)$$

STANDARD DEVIATIONS OF ORIENTATION RESOLUTIONS

$$\sigma_{\overline{\sigma}_{Yaw}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{\sigma}_{Yaw}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{\sigma}_{Yaw}} = \left(\sigma_{Yaw\,i} - \overline{\sigma}_{Yaw}\right)$$

$$\sigma_{\overline{\sigma}_{Pitch}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{\sigma}_{Pitch}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{\sigma}_{Pitch}} = \left(\sigma_{Pitch\,i} - \overline{\sigma}_{Pitch}\right)$$

$$\sigma_{\overline{\sigma}_{Roll}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{\sigma}_{Roll}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{\sigma}_{Roll}} = \left(\sigma_{Roll\,i} - \overline{\sigma}_{Roll}\right)$$

$$\sigma_{\overline{\sigma}_{C}} = \left[\frac{1}{(n-1)}\sum_{i=1}^{i=n} e_{i\overline{\sigma}_{C}}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{i\overline{\sigma}_{C}} = \left(\sigma_{C\,i} - \overline{\sigma}_{C}\right)$$

Resolution Versus Servo Track Operation. This test is a follow on to the resolution tests to compare tracker data output with the U500 system powered on versus off. This allows for an identification of possible interference effects of the track servo motor and electronics with the tracking system under test. Possible sources of interference are acoustic, electrical, and mechanical. Acoustic artifacts would mainly affect ultrasonic tracking systems, electrical artifacts (including magnetic and Radio Frequency (RF) emissions) and mechanical artifacts (vibrations) could affect every type of tracking system by interfering with the sensor(s)/emitter(s) directly or the tracking system electronics.

To check for effects of the U500 servo motor and electronics on the tracker, resolution tests (See Resolution Test Procedures) should be performed on a stationary tracking target with the tracking system operating in each of three modes: powered off, powered on stationary, and powered on moving. This analysis involves repeating the resolution measurement procedure and looking for differences in the resolution values in each of the three states. Since the resolution measurement procedure of the previous section were taken with the U500 system powered off, these follow on tests only require resolution measurements with the U500 powered on stationary, and powered on moving. This analysis should take into account a number of resolution samplings to insure that the stability of resolution values are not a factor in the data taken in each of the three track operating modes. Any effects noted in these tests will have an impact on the static and dynamic measurements to be made later.

Static Accuracy Tests

The static accuracy analyses include:

- Static Position Accuracy Analysis
- Static Position Error Plot
- Static Orientation Stability Analysis.
- Static Orientation Stability Plot.

These static accuracy tests are performed after the physical track alignment and coordinate system alignment have been performed. The physical alignment is the process of physically positioning the U500 track to align it to the coordinate axes of the tracking system. Since reducing the physical track alignment errors to the level of the tracking system accuracy is difficult, a mathematical alignment is also performed. The purpose of this mathematical coordinate system alignment is to translate and rotate the tracking system position coordinates into a new coordinate system with an origin at the track home position and a y-axis that follows the track axis. Tracker output is converted to this new track aligned coordinate system before being used in the static accuracy calculations. (see Track and Tracker Alignments in the General Tracking Tests Discussion section). In this track aligned coordinate system, the target's y-coordinates should follow the track's encoder output as the target (attached to the track stage) moves along the track axis. This allows for a one dimensional analysis of the tracking system accuracy. Note that this accuracy analysis is not an absolute measure, but is relative to the track home position and the distance moved along the track.

The track stage, starting at the relative track home position, (0, 0, 0), is set to move to an endpoint on the track in a user defined number of constant displacement increments (e.g., 100 mm). After each movement, a 5 second delay in sampling is used to wait for the track stage and target tower structure to stabilize. At each increment of the track stage, the tracker under test is requested to take 20 data samples of position/orientation. The track stage is incrementally moved until the track endpoint is reached. These sets of 20 samples at each static stage position are the raw test data for the static accuracy tests.

Static Position Accuracy Analysis. The 20 position data samples taken at each position are statistically analyzed using the equations in Table 6. Since the target motion is in one dimension along the U500 track axis, the x and z positions and means are only meaningful in terms of cross axis position errors. The x and z-axis means and position errors are calculated to include these cross axis effects in the radial static position accuracy.

Referring to Table 6, the Static Position Means are the average of the position samples taken at each static position. These means, $(\overline{Xs}, \overline{Ys}, \overline{Zs})$, give the averaged position of the target within the track aligned coordinate system. There is a Static Position Mean value for each of the static positions used in the static accuracy tests. Each $\overline{Ys}$ mean position indicates the averaged position of the target along the track's axis. Ideally, as the track stage moves to each position, the tracking positions provided by the tracking system should only vary in y, with x and z remaining at zero.

The Static Position Errors are calculated using the Static Position Means and a relative measure of the actual target position derived from the U500 track output. The reference for the Static Position Errors is the optical encoder position output from the U500 track. The derived track positions (X_T, Y_T, Z_T) used in Table 6 are formed by adding the cumulative track movement to the y coordinate of the track origin of (0, 0, 0). Calculating this error term using the track encoder output provides for the accuracy relative to the initial track origin or home position. Note that when the position standard deviations are calculated, the error terms are calculated using the U500 reported position and the tracker output in the track aligned coordinate system.

Once the set of Static Position Errors are calculated for each stop along the track, these errors are used to calculate the Mean Static Position Errors. The Mean Static Position Error is the average of the individual static position errors along the target's path. Using the Static Position Errors and the Mean Static Position Errors, the Static Position Standard Deviations, (σ_{SX}, σ_{SY}, σ_{SZ}), are calculated for each axis. These one dimensional error and standard deviation values are then combined to form the Radial Static Position Error, $\overline{Res}$, and the Radial Static Position Standard Deviation, σ_{SR}, which adds in the x and z cross axis effects. The combination of these two values, $\overline{Res}$ and σ_{SR}, constitute the Radial Static Position Accuracy measure.

The accuracy calculations by the equations of Table 6 are only significant for each particular physical alignment and position of the U500 track relative to the tracking system. The static accuracy calculations can be repeated for several orientations of the U500 track axis relative to the tracking system's coordinate system. Repositioning the track will allow another static accuracy test to be performed along a second position/alignment of the tracking system. All that is required is to perform the physical and coordinate system alignment procedures, then repeat the static tests. Additional orientations of the track relative to the tracker coordinate system may be performed as needed.

Table 6. Static Position Accuracy Calculations

STATIC POSITION MEANS

$$\overline{X}_{S\,j} = \frac{1}{n}\sum_{i=1}^{n} X_{S\,i}\text{, where } X_{S\,i} \text{ are the } n\ X_S \text{ tracker values for j = 1,M positions}$$

$$\overline{Y}_{S\,j} = \frac{1}{n}\sum_{i=1}^{n} Y_{S\,i}\text{, where } Y_{S\,i} \text{ are the } n\ Y_S \text{ tracker values for j = 1,M positions}$$

$$\overline{Z}_{S\,j} = \frac{1}{n}\sum_{i=1}^{n} Z_{S\,i}\text{, where } Z_{S\,i} \text{ are the } n\ Z_S \text{ tracker values for j = 1,M positions}$$

STATIC POSITION ERRORS

$$Xes_j = \left(\overline{X}_{S_j} - X_T\right),\quad \text{for j = 1 to M; } X_T \text{ is U500 derived position}$$

$$Yes_j = \left(\overline{Y}_{S_j} - Y_T\right),\quad \text{for j = 1 to M; } Y_T \text{ is U500 derived position}$$

$$Zes_j = \left(\overline{Z}_{S_j} - Z_T\right),\quad \text{for j = 1 to M; } Z_T \text{ is U500 derived position}$$

MEAN STATIC POSITION ERRORS

$$\overline{X}es = \frac{1}{M}\sum_{j=1}^{M} Xes_j\text{, for each of the M static } X_{es} \text{ position errors}$$

$$\overline{Y}es = \frac{1}{M}\sum_{j=1}^{M} Yes_j\text{, for each of the M static } Yes \text{ position errors}$$

$$\overline{Z}es = \frac{1}{M}\sum_{j=1}^{M} Zes_j\text{, for each of the M static } Zes \text{ position errors}$$

STATIC POSITION STANDARD DEVIATION

$$\sigma_{S_X} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jX}^2\right]^{\frac{1}{2}},\quad \text{where } e_{jX} = \left(Xes_j - \overline{X}es\right)$$

$$\sigma_{S_Y} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jY}^2\right]^{\frac{1}{2}},\quad \text{where } e_{jY} = \left(Yes_j - \overline{Y}es\right)$$

$$\sigma_{S_Z} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jZ}^2\right]^{\frac{1}{2}},\quad \text{where } e_{jZ} = \left(Zes_j - \overline{Z}es\right)$$

RADIAL STATIC POSITION ACCURACY

$$\overline{R}es = \left(\overline{X}es^2 + \overline{Y}es^2 + \overline{Z}es^2\right)^{\frac{1}{2}}\ ;\qquad \sigma_{S_R} = \left(\sigma_{S_X}^2 + \sigma_{S_Y}^2 + \sigma_{S_Z}^2\right)^{\frac{1}{2}}$$

The Radial Static Position Accuracy values for several track orientation can form a Mean Radial Static Position Accuracy measure by combining a number, n, of Radial Static Position Error and Radial Static Position Standard Deviations measures via equations of the form:

$$\overline{R}_{es_M} = \frac{\sum_{i=1}^{n} \overline{R}_{es_i}}{n}\text{, and}\qquad \sigma_{SR_M} = \frac{\sum_{i=1}^{n} \sigma_{SR_i}}{n}\ .$$

Static Position Error Plot. The static position errors calculated during the static accuracy tests can be plotted to look at the error of the tracking system. The static position errors are calculated at each of the M incremental positions of the target during the static accuracy test. A summary position accuracy output file (with filetype .pos.std) is provided by the tracker test program and includes a tab delimited table of position error versus track position for import into an Excel spreadsheet. These errors are then plotted on a graph with the derived track position, Y_T, along the x-axis and the position error, Y_{es_j}, along the y-axis. Only the Y_{es_j} static position errors are plotted because they are the only errors directly referenced to the track position outputs. The Static Accuracy Error Plot provides a view of the point to point variation in the tracker position outputs over the length of the track for the specific track orientation and position.

Static Orientation Stability Analysis. During the static accuracy tests, orientation data is recorded if the tracker provides 6DOF. The data recorded consists of a set of yaw, pitch, and roll angles taken at each incremental stop of the target. While the ability to change the orientation of the target is not currently a capability of the test equipment, an analysis of the orientation stability during this test can be made. Note that while the target is being repositioned by the track stage movement, the rigid mounting of the target to the stage prevents changes in the target's yaw, pitch, and roll angles. As the target moves from position to position during the static accuracy test, the yaw, pitch, and roll angles should remain the same as those recorded during the track alignment procedure. Therefore, the orientation stability analysis is performed by using the initial yaw, pitch, and roll angles as a reference. Comparisons are made between this reference and the Static Orientation Mean at each subsequent stop of the track stage. The orientation calculations are similar to static position accuracy calculations of Table 6, and are defined in Table 7. The set of Static Orientation Errors is averaged to provide the Mean Static Orientation Error for the yaw, pitch, and roll angles. The Static Orientation Standard Deviation for each angle is a calculation involving the Mean Static Orientation Error and each Static Orientation Error. Similar to the Orientation Resolution calculations, the yaw and pitch values of the Mean Static Orientation Errors and the Static Orientation Standard Deviations can be combined to form a Conic Static Orientation Error and a Conic Orientation Standard Deviation value. The combination of these error and standard deviation values forms the Conic Static Orientation Stability, which is a measure of the angular pointing stability in yaw and pitch. The ideal result of the calculations of Table 7 would be Static Orientation Error values of zero leading to Mean Static Orientation Error and Static Orientation Standard Deviation values of zero.

The track can be placed in several position/orientations relative to the tracker coordinate system with the static orientation calculations repeated to form the Mean Conic Orientation Stability. The Conic Static Orientation Error, $\overline{C}_{es_M}$, and the Conic Static Orientation Standard Deviation, σ_{sc_M}, are averaged to form the Mean Conic Orientation Stability via:

$$\overline{C}_{es_M} = \frac{\sum_{i=1}^{n} \overline{C}_{es_i}}{n} \quad \text{and} \quad \sigma_{sc_M} = \frac{\sum_{i=1}^{n} \sigma_{sc_i}}{n},$$

where n is the number of track position alignments.

Table 7. Static Orientation Stability Calculations

STATIC ORIENTATION MEANS

$\overline{Yaw}_{s_j} = \frac{1}{n}\sum_{i=1}^{n} Yaw_{s_i}$, where Yaw_{s_i} are the n Yaw_s tracker values for j = 1, M positions

$\overline{Pitch}_{s_j} = \frac{1}{n}\sum_{i=1}^{n} Pitch_{s_i}$, where $Pitch_{s_i}$ are the n $Pitch_s$ tracker values for j = 1, M positions

$\overline{Roll}_{s_j} = \frac{1}{n}\sum_{i=1}^{n} Roll_{s_i}$, where $Roll_{s_i}$ are the n $Roll_s$ tracker values for j = 1, M positions

STATIC ORIENTATION ERRORS

$Yawes_j = \left(\overline{Yaw}_{s_j} - \overline{Yaw}_{s_1}\right)$, for j = 1 to M; $\overline{Yaw}_{s_1}$ is the initial Static Yaw Mean

$Pitches_j = \left(\overline{Pitch}_{s_j} - \overline{Pitch}_{s_1}\right)$, for j = 1 to M; $\overline{Pitch}_{s_1}$ is the initial Static Pitch Mean

$Rolles_j = \left(\overline{Roll}_{s_j} - \overline{Roll}_{s_1}\right)$, for j = 1 to M; $\overline{Roll}_{s_1}$ is the initial Static Roll Mean

MEAN STATIC ORIENTATION ERRORS

$\overline{Yaw}_{es} = \frac{1}{M}\sum_{j=1}^{M} Yaw_{es_j}$, for each of the M static Yaw_{es} orientation errors

$\overline{Pitch}_{es} = \frac{1}{M}\sum_{j=1}^{M} Pitch_{es_j}$, for each of the M static $Pitch_{es}$ orientation errors

$\overline{Roll}_{es} = \frac{1}{M}\sum_{j=1}^{M} Roll_{es_j}$, for each of the M static $Roll_{es}$ orientation errors

STATIC ORIENTATION STANDARD DEVIATIONS

$\sigma_{S_{Yaw}} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e^2_{jYaw}\right]^{\frac{1}{2}}$, where $e_{jYaw} = \left(Yaw_{es_j} - \overline{Yaw}_{es}\right)$

$\sigma_{S_{Pitch}} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e^2_{jPitch}\right]^{\frac{1}{2}}$, where $e_{jPitch} = \left(Pitch_{es_j} - \overline{Pitch}_{es}\right)$

$\sigma_{S_{Roll}} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e^2_{jRoll}\right]^{\frac{1}{2}}$, where $e_{jRoll} = \left(Roll_{es_j} - \overline{Roll}_{es}\right)$

CONIC STATIC ORIENTATION STABILITY

$\overline{C}_{es} = \left(\overline{Yaw}_{es}^{\,2} + \overline{Pitch}_{es}^{\,2}\right)^{\frac{1}{2}}$; $\sigma_{SC} = \left(\sigma^2_{S_{Yaw}} + \sigma^2_{S_{Pitch}}\right)^{\frac{1}{2}}$

Static Orientation Stability Plot. The static orientation errors can be plotted to show the effect of the incremental movements of the track stage at each of the M positions of the static accuracy tests. The tracker test program provides an output file that is a summary of the orientation data. This file is user-named to indicate the test performed (e.g., static) with an automatically appended filetype of .rot.std. This file includes a tab delimited table containing the static orientation errors at each of the M stage positions. Importing this file into Excel, a graph of track position on the x-axis versus static orientation errors on the y axis can be plotted to show the changes in orientation due to the track movement.

Dynamic Accuracy Tests

The Dynamic Accuracy analyses include:

- Dynamic Position Accuracy Analysis
- Dynamic Position Error Plot
- Dynamic Lag Analysis
- Dynamic Position Error and Lag Plot
- Dynamic Orientation Stability Analysis
- Dynamic Orientation Stability Plot

The measurement of dynamic accuracy involves taking a continuous set of data samples from the tracking system under test while the target is moving. The target is mounted on the U500 track stage which moves from its origin to the track end in three phases. As in the Static Accuracy Tests, the U500 track is physically aligned within the tracking system motion volume and the tracking system 3D coordinates are mathematically aligned to the track coordinate system.

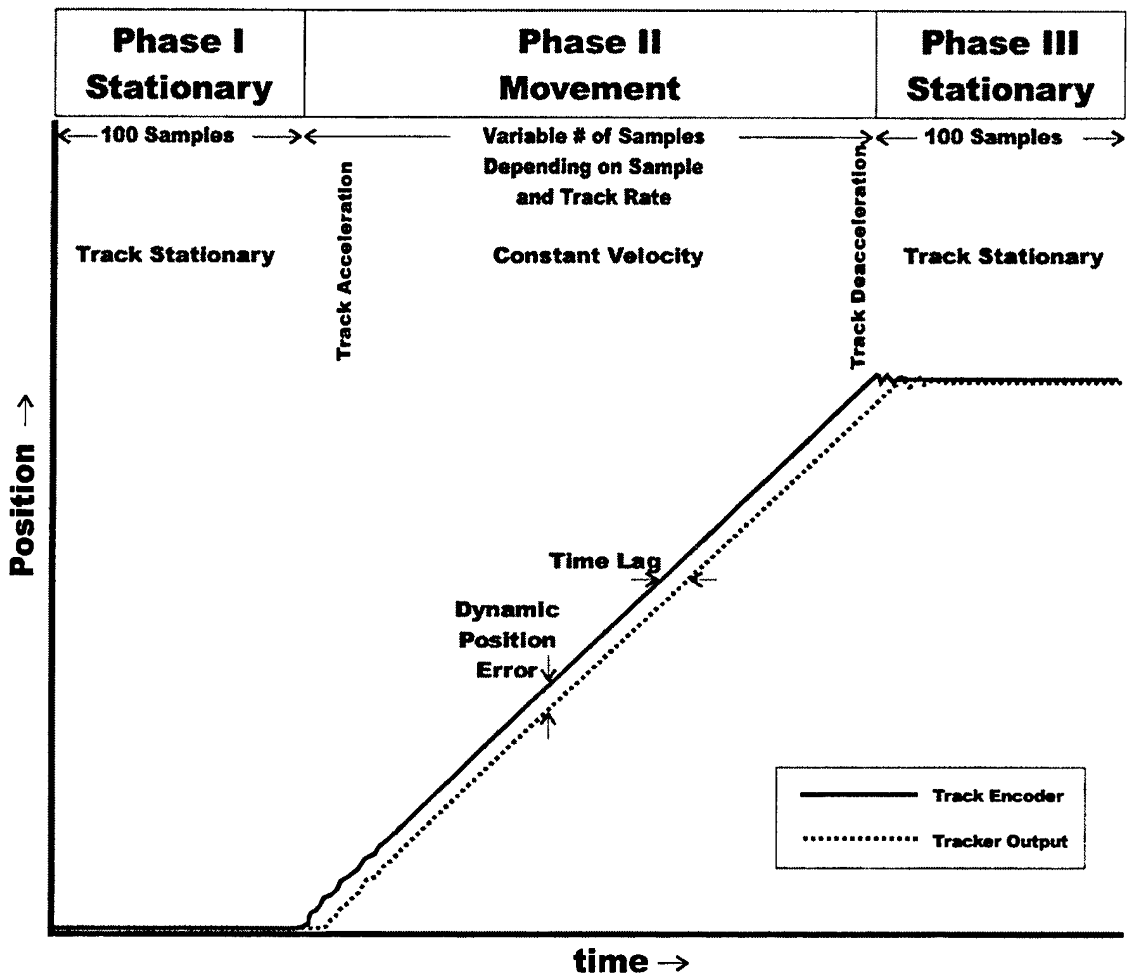

Figure 9. Dynamic Accuracy Test Phases.

The three phases of the dynamic accuracy test are depicted in Figure 9. Each phase of the dynamic test is performed automatically via the AWST tracker test software. During the first phase, the track stage is positioned at the home position and the tracking system is instructed to begin a continuous output of data to the computer. After the time required for the AWST tracker test program to store 100 tracker data samples during the stationary phase I, phase II starts with the track stage signaled to start moving. The test software continues to record tracking data during the movement of phase II. The number of tracker data samples taken during phase II is variable and depends on the speed of the track and the tracker sample rate. For a fixed tracker sample rate, faster track speeds would result in fewer data samples. Conversely, for a fixed track speed, faster sample rates would result in more data samples. After the track stage stops at the endpoint, phase III involves continuously taking another 100 tracker data samples while the track stage is stationary. The stationary tracking data taken during phases I and III are intended to allow inspection of the data for any errors, offsets, or noise artifacts. These dynamic tests are intended to look at the performance of the tracking system under conditions that approximate actual use in a small arms weapons simulator.

During the three phases of the dynamic accuracy tests, the software stores the tracker data, as well as the track encoder position data and a time stamp indicating when the data was received. The track stage position is read from the U500 controller card registers after each tracker data sample arrives from the tracking system being tested. Following the reading of the U500 registers, the timer card is read to time stamp each data sample. The combination of the track position data and time stamp allows for the velocity of the track to be calculated based on sample to sample position and time differences.

The collection of tracker data is continuous from the stationary phase I, through the phase II movement, and into the stationary phase III. Since the purpose of this dynamic test is to examine the output of a tracker during target movement, the only data used for the dynamic analysis is the phase II movement data. This includes the Dynamic Position Accuracy Analysis and Plot, Dynamic Lag Analysis and Plot, and Dynamic Orientation Stability Analysis and Plot. The identification of phase II target movement data samples within the three phase data set is simplified by adding an index variable to each sample set. This index is reset to 1 at the start of each dynamic phase, with the phase II data starting at the index value of 1 following the 100 phase I samples.

Software Timing for Track Position and Time Stamping. For the dynamic testing methods to follow, and particularly for the dynamic lag analyses, the software and hardware time lags introduced by the track and timer hardware need to be identified. Timing data was gathered for the tasks of reading the target data from the serial buffer, reading the track position encoder, reading the timing card, and processing the data. This data was for a tracking setup that used a serial port with a continuous transfer method for ASCII data. The means and standard deviations of this timing data are provided in Table 8. Table 8 indicates that reading the serial buffer was the most time consuming task at a mean of 2.1 msec. The remaining task timings in decreasing order are: reading the track encoder, reading the PC-TIO-10 timer, and the processing/storing of the data. All together, the total summed time for these tasks amounts to approximately 3.8 msec ± a standard deviation of 0.33 msec.

Table 8. AWST Timing Statistics

Descriptive Statistics	*IS600 Read (Serial Buffer)*	*Read Track Encoder*	*Read PCTIO-10 Timer*	*Process Data*	*Summed Cycle Time*
Mean	0.00210558	0.00085929	0.00054814	0.00027238	0.00378539
Standard Error	0.00000519	0.00001542	0.00000207	0.00000207	0.00001895
Median	0.00209450	0.00077400	0.00055500	0.00025600	0.00367850
Mode	0.00202700	0.00069400	0.00056200	0.00025100	0.00370900
Standard Deviation	0.00008891	0.00026436	0.00003545	0.00003546	0.00032488

Note 1: Timing values have units of seconds   Note 2: Data is minus 20+ msec encoder read samples

The serial buffer read time of 2.1 msec is a significant part of delays in the AWST tracker test program. This buffer read time would always be a part of any tracker to host transfer and can be considered as part of the tracker lag. However, the serial buffer read time does contribute to the time difference between the tracker data and the U500 track position. The offset in time between the tracker position data and the U500 track position data can be calculated by combining the serial buffer read time with the timing for acquiring the position of the U500 track. The U500 mean track encoder read time is listed in Table 8 as 0.86 msec. However, consider that the U500 controller card, a proprietary interface card located on the host's ISA bus, has its registers updated every 250 μsec with servo-controller position data. When the command to read the track encoder is issued by the host computer, the track interface latches and holds the current track position. While it takes approximately 0.86 msec to read the data from U500 controller, the data received is locked in within 0.25 msec of the start of the data read. This latching is internal to the Unidex interface and occurs within the 250 μsec register update cycle. The net timing difference between the tracker data and the track position data is in the neighborhood of 2.1 msec plus 0.25 msec for a total of 2.35 msec. For most tracking systems, this measurement delay is minimal in terms of the lag of the tracking system, which may range from 5 to 100 msec.

The remaining critical timing consideration, in terms of relative timing of dynamic position data, is the time stamping via the PC-TIO-10 timer card. This read timing is relatively short at 0.55 msec with a standard deviation of 0.035 msec. The time stamp is consistently delayed about 0.55 msec behind the finish of the U500 track data reads and has little variation. Adding in the U500 track encoder read time of 0.86 msec, the time stamp is 1.41 msec behind the reading of the tracker data with a combined standard deviation of 0.3 msec. Because the time stamping occurs at a constant time offset, it has little effect on the dynamic analyses. The effect is to shift the relative time value recorded, but not change the magnitude of the time difference between time stamps.

Dynamic Position Accuracy Analysis. The major difference between the dynamic accuracy and the static accuracy analyses is that multiple data samples are not taken at each position. Since the target is moving, data is taken while movement occurs over a range of positions that depends on track speed and tracker sample rate. There is no averaging of multiple data samples at each position to calculate a dynamic position mean. The position data samples (X_{Dj}, Y_{Dj}, Z_{Dj}) taken during the dynamic test are statistically analyzed using the equations of Table 9. Note that the position coordinates for this analysis are in the track aligned coordinate system, where the origin is the U500 track home position and the y-axis follows the track axis. Similar to the static tests, only the target y-axis coordinates should change as the track stage moves. The x and z-axis coordinates are used to include cross-axis error effects in the radial dynamic position error and accuracy value.

Referring to Table 9, the Dynamic Position Errors are calculated using the phase II position coordinates and the derived track position. The derived position coordinate is calculated by adding the track's encoder output to the track origin of (0,0,0). The Dynamic Position Errors are a measure of the net position difference between the positions reported by the U500 track and the tracking system being tested, with the track position representing the actual position. This net position difference is a combination of the error in the tracker's calculation of the target position, the target sampling time, the position calculation time, and the data output time. It is important to note that the Dynamic Position Error includes any static position errors present in the tracking system. Compensating methods can be used to reduce the static position error and, in turn, reduce the dynamic position error. Removing the static position error from the dynamic position error will produce a true picture of the dynamic lag.

The Dynamic Position Errors are averaged over the phase II motion data set to find the Mean Dynamic Position Errors for each x, y, and z coordinate. These mean errors are combined to form the Radial Dynamic Position Error. They are also used as references to calculate the standard deviations of the Dynamic Position Errors for each coordinate axis. These error and standard deviation values provide the x, y, and z Dynamic Position Accuracy values that are combined to form the Radial Dynamic Position Accuracy value. Similar to the static position accuracy procedure, the track can be repositioned for additional testing. The calculations from Table 9 are then repeated and the results combined as the Mean Radial Dynamic Position Error and the Mean Radial Dynamic Position Standard Deviation via:

$$\overline{R}_{eD_M} = \frac{\sum_{i=1}^{n} \overline{R}_{eD_i}}{n} \text{, and} \qquad \sigma_{DR_M} = \frac{\sum_{i=1}^{n} \sigma_{DR_i}}{n}.$$

Table 9. Dynamic Position Accuracy Calculations

DYNAMIC POSITION ERRORS

$$Xe_{D_j} = \left(X_{D_j} - X_T\right), \quad \text{for } j = 1 \text{ to } M;\ X_T \text{ is U500 derived position}$$

$$Ye_{D_j} = \left(Y_{D_j} - Y_T\right), \quad \text{for } j = 1 \text{ to } M;\ Y_T \text{ is U500 derived position}$$

$$Ze_{D_j} = \left(Z_{D_j} - Z_T\right), \quad \text{for } j = 1 \text{ to } M;\ Z_T \text{ is U500 derived position}$$

MEAN DYNAMIC POSITION ERRORS

$$\overline{X}e_D = \frac{1}{M}\sum_{j=1}^{M} X_{eD_j}, \quad \text{for each of the } M \text{ dynamic } X_{eD} \text{ position errors}$$

$$\overline{Y}e_D = \frac{1}{M}\sum_{j=1}^{M} Y_{eD_j}, \quad \text{for each of the } M \text{ dynamic } Y_{eD} \text{ position errors}$$

$$\overline{Z}e_D = \frac{1}{M}\sum_{j=1}^{M} Z_{eD_j}, \quad \text{for each of the } M \text{ dynamic } Z_{eD} \text{ position errors}$$

DYNAMIC POSITION STANDARD DEVIATIONS

$$\sigma_{DX} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jX}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{jX} = \left(Xe_{D_j} - \overline{X}e_D\right)$$

$$\sigma_{DY} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jY}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{jY} = \left(Ye_{D_j} - \overline{Y}e_D\right)$$

$$\sigma_{DZ} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jZ}^2\right]^{\frac{1}{2}}, \quad \text{where } e_{jZ} = \left(Ze_{D_j} - \overline{Z}e_D\right)$$

RADIAL DYNAMIC POSITION ACCURACY

$$\overline{R}e_D = \left(\overline{X}e_D^{\,2} + \overline{Y}e_D^{\,2} + \overline{Z}e_D^{\,2}\right)^{\frac{1}{2}} \quad ; \qquad \sigma_{DR} = \left(\sigma_{DX}^2 + \sigma_{DY}^2 + \sigma_{DZ}^2\right)^{\frac{1}{2}}$$

Dynamic Position Error Plot. The Dynamic Position Errors calculated during the dynamic accuracy tests can graphically show the dynamic accuracy errors along the track path. The Dynamic Position Errors are calculated at each sampling of the U500 track and target during the dynamic accuracy test. These position errors are summarized in a dynamic test output file that has a filetype of .pos.std. The errors are plotted on a graph with the derived track position, Y_T, along the x-axis and the dynamic position errors, Y_{eD_j}, along the y-axis. The Y_{eD_j} dynamic position errors are the only errors plotted because they are directly referenced to the track position outputs. The Dynamic Position Error Plot provides a view of the point to point variation in the tracker position outputs over the length of the track at a specific track orientation and position.

Dynamic Lag Analysis. The lag of a tracking system is due to the combined time required for the tracking system to sample the sensors, calculate the position and orientation data, and then output the data. The effect of lag is that once the target starts moving, the tracking system data for the target will fall behind the actual target position. In the test track setup, the track encoder reading provides the actual position of the target. In the absence of lag, the tracking system and U500 track outputs would be the same. With lag in the tracking system, the tracking system position output versus the U500 track output will show the target position to be behind the track stage. This difference in position is dependent on the tracking system time lag. The dynamic lag analysis uses this position difference to calculate the dynamic lag.

The dynamic lag analysis is performed within an Excel spreadsheet. The tracking test program outputs a user named file with a filetype of .txt (e.g., IS600_dynamic.txt) that contains every sample taken during the dynamic test. The data sample includes the following tab delimited data: sample index, time stamp, track encoder position, target position (x, y, z), and target orientation (yaw, pitch, roll). After the output file is imported into an Excel spreadsheet, additional columns of data are added by performing calculations on the original data. These calculations include: time increment between samples (Δt), track encoder position change between samples (ΔEncoder), track velocity (V_{track}), target position change between samples (Δy), Dynamic Position Error (Pos. Error), target orientation changes between samples (Δyaw, Δpitch, Δroll), and the time lag between the track and the target (Lag_{time}).

The procedure to calculate the phase II time lag starts with finding the difference between the track position and the target y coordinate positions within each data sample. The difference is the Dynamic Position Error and is calculated by the following equation:

$$\text{Dynamic Position Error} = \text{target y coordinate} - \text{track position}\ .$$

Using the time stamp values and the track y coordinate values, the change in time and position from one track sample to the next is used to calculate the velocity of the stage at each position sample (i.e., $V_{track} = \Delta y/\Delta t$). This velocity and the position error are then used to calculate the time difference that would lead to the position difference. This time difference is the tracker lag for the position data, Lag_{time}, and is calculated by the following equation:

$$Lag_{time} = \text{Dynamic Position Error} / V_{track}\ .$$

The time lag calculation can be understood by looking back to the phase II segment of the dynamic accuracy test depicted in Figure 9. The Dynamic Position Error is noted in the figure as a vertical displacement between the track encoder curve and the tracker curve. This displacement is along a line parallel to the position axis and marks a single point in time. Note that the displacement between the two curves has been exaggerated for clarity. The calculation of Lag_{time} can be viewed as a process of sliding forward in time up the tracker curve until a position is reached that equals the previously noted track encoder value. At this point, the horizontal displacement between the points on the two curves is the time that the target would take, traveling at the same velocity, to catch up to the track. This is the time that the target lags the track, assuming no change in velocity. Using the current velocity of the track, V_{track}, the time to travel the required travel distance (the Dynamic Position Error) is calculated. This time is the value associated with Lag_{time}.

Correcting Dynamic Lag for Static Offsets. The lag value calculation includes position errors introduced by several factors associated with the tracking system timing. These factors include the tracking system's sampling, calculation, and data transfer times. An undesired effect on the Lag_{time} calculation is error introduced by uncorrected static position accuracy errors. Negative static position errors will increase the apparent lag time by increasing the dynamic position error. Positive static position errors will reduce the apparent lag by reducing the dynamic position error. Large positive static position errors can reduce the dynamic position error to the point that the target position moves ahead of the track position, causing an apparent time lead instead of lag. To get a true reading on the tracker lag, these static position errors must be removed from the lag value calculations.

The removal of static position errors from the dynamic lag is performed using the results of the static position accuracy tests. To perform this correction, the static accuracy tests are performed first with the same track position and orientation as the dynamic test to be corrected. The Static Position Errors are then calculated in order to correct the Dynamic Position Errors. However, the sampling positions of the track stage for the static tests and the dynamic tests are not identical. Therefore, a curve fitting method was used for finding the static position errors to subtract from the dynamic position errors. The incremental static position errors versus track position were used to derive an equation of the form:

$$\text{Static Position Error} = f(\text{Track Position}).$$

This equation describes the trend of the static position error over the length of the track stage. The required order of the equation depends on the actual static position error data, though a first or second order equation is usually adequate. A graph of the static position errors, created by importing the static position error data into an Excel spreadsheet, is used in creating an Excel trendline that provides an appropriate f(Track Position) equation.

To apply the correction for static position errors, the f(Track Position) equation is used to calculate the static position error for the track position associated with each dynamic position error. This interpolated static position error is subtracted from the dynamic position error to provide a corrected dynamic position error for each dynamic sample. The lag calculations are then performed using this corrected dynamic position error to arrive at corrected lag times for each dynamic sample. The corrected Dynamic Position Errors and lag values for each of the dynamic samples are then averaged to provide an average dynamic position error, Avg. $Error_{Corr}$, and an averaged dynamic lag, Avg. Lag_{Corr}, for the entire dynamic test set.

Dynamic Position Error and Lag Plot. The data from the dynamic lag analysis procedure and the correction process is used to enhance the Dynamic Position Error Plot. In addition to the averaged dynamic position error and lag, this data includes each sample's $\mathrm{Lag}_{\mathrm{time}}$, corrected Dynamic Position Error, and corrected $\mathrm{Lag}_{\mathrm{time}}$. Adding this additional dynamic sample data to the Dynamic Position Error Plot provides a view of the relationships between the uncorrected and corrected position errors and time lags. The Dynamic Position Error and Lag plot should have dual y-axes, one for position error and the other for lag time. The x-axis would typically represent the dynamic test time, but may be scaled for dynamic track position. The plot would be completed by pasting the Avg. $\mathrm{Error}_{\mathrm{Corr}}$ and Avg. $\mathrm{Lag}_{\mathrm{Corr}}$ values onto the graph.

Dynamic Orientation Stability Analysis. For 6DOF trackers, recorded orientation data is used to evaluate the Dynamic Orientation Stability. The equations are listed in Table 10, and basically follow the logic of the Static Orientation Stability Analysis with two exceptions. The first exception is that there is no averaging of the orientation values during the dynamic phase II, since the data is taken continuously with only one data sample per position. The second exception concerns the Dynamic Orientation Errors, where the reference for calculating the errors is the mean of the 100 phase I orientation values taken while the target is at the track home position. By using the mean of these 100 orientation values, the dynamic errors are referenced to an initial orientation that is stable.

Table 10 contains the equations for the Dynamic Orientation Stability Analysis. The Dynamic Orientation Errors are used to find the Mean Dynamic Orientation Errors for the phase II movement of the track. The Dynamic Orientation Standard Deviations values are then calculated using the Mean Dynamic Orientation Errors as references in standard deviation calculations of the Dynamic Orientation Errors. The Conic Dynamic Orientation Error, $\overline{C}_{eD}$, is calculated by combining the Mean Dynamic Orientation Error yaw and pitch values. The Conic Dynamic Orientation Standard Deviation, σ_{DC}, is calculated by combining the yaw and pitch values of Dynamic Orientation Standard Deviations. These conic error and standard deviation values, $\overline{C}_{eD}$ and σ_{DC}, form the Conic Dynamic Orientation Stability.

The track can be placed in several positions/orientations relative to the tracker coordinate system and the static orientation calculations repeated to form the Mean Conic Dynamic Stability. The Mean Conic Dynamic Orientation Error, $\overline{C}_{eD_M}$, and the Mean Conic Dynamic Orientation Standard Deviation, σ_{DC_M}, are combined by the equations:

$$\overline{C}_{eD_M} = \frac{\sum_{i=1}^{n} \overline{C}_{eD_i}}{n} \quad \text{and} \quad \sigma_{DC_M} = \frac{\sum_{i=1}^{n} \sigma_{DC_i}}{n},$$

where n is the number of track positions/orientations tested.

Table 10. Dynamic Orientation Stability Calculations

DYNAMIC ORIENTATION ERRORS

$$Yaw_{eDj} = \left(Yaw_{Dj} - \overline{Yaw}_{S_1}\right) \quad , \text{ for } j = 1 \text{ to M; } \overline{Yaw}_{S_1} \text{ is the initial Static Yaw Mean}$$

$$Pitch_{eDj} = \left(Pitch_{Dj} - \overline{Pitch}_{S_1}\right) \quad , \text{ for } j = 1 \text{ to M; } \overline{Pitch}_{S_1} \text{ is the initial Static Pitch Mean}$$

$$Roll_{eDj} = \left(Roll_{Dj} - \overline{Roll}_{S_1}\right) \quad , \text{ for } j = 1 \text{ to M; } \overline{Roll}_{S_1} \text{ is the initial Static Roll Mean}$$

MEAN DYNAMIC ORIENTATION ERRORS

$$\overline{Yaw}eD = \frac{1}{M}\sum_{j=1}^{M} Yaw_{eDj} \quad , \text{for each of the M dynamic } Yaw_{eD} \text{ orientation errors}$$

$$\overline{Pitch}eD = \frac{1}{M}\sum_{j=1}^{M} Pitch_{eDj} \quad , \text{for each of the M dynamic } Pitch_{eD} \text{ orientation errors}$$

$$\overline{Roll}eD = \frac{1}{M}\sum_{j=1}^{M} Roll_{eDj} \quad , \text{for each of the M dynamic } Roll_{eD} \text{ orientation errors}$$

DYNAMIC ORIENTATION STANDARD DEVIATIONS

$$\sigma_{D\,Yaw} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jYaw}^2\right]^{\frac{1}{2}} \quad , \text{ where } e_{jYaw} = \left(Yaw_{eDj} - \overline{Yaw}_{eD}\right)$$

$$\sigma_{D_{Pitch}} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{j\,Pitch}^2\right]^{\frac{1}{2}} \quad , \text{ where } e_{j\,Pitch} = \left(Pitch_{eDj} - \overline{Pitch}_{eD}\right)$$

$$\sigma_{D_{Roll}} = \left[\frac{1}{(M-1)}\sum_{j=1}^{M} e_{jRoll}^2\right]^{\frac{1}{2}} \quad , \text{ where } e_{jRoll} = \left(Roll_{eDj} - \overline{Roll}_{eD}\right)$$

CONIC DYNAMIC ORIENTATION STABILITY

$$\overline{C}_{eD} = \left(\overline{Yaw}_{eD}^{\,2} + \overline{Pitch}_{eD}^{\,2}\right)^{\frac{1}{2}} \quad ; \quad \sigma_{DC} = \left(\sigma_{D_{Yaw}}^2 + \sigma_{D_{Pitch}}^2\right)^{\frac{1}{2}}$$

Dynamic Orientation Stability Plot. The dynamic orientation errors are plotted to show the effect of the track stage movements on the target's orientation during the dynamic accuracy tests. Dynamic orientation data from the tracker test program is output to a file with a filetype of .rot.std and a user provided filename that indicates the test performed (e.g., dynamic). This file contains a statistical summary of the orientation data. Also included is a tab delimited table containing the time stamp, encoder position, and the yaw, pitch, and roll dynamic orientation errors for each sample taken during the dynamic test. Importing this file into Excel, a graph can be plotted to show the changes in orientation due to the track movement. This graph would have track position on the x-axis and the dynamic orientation errors in degrees on the y axis. The statistical summary data from this file can be pasted onto the graph to show the orientation stability.

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CONCLUSIONS AND RECOMMENDATIONS

This report has documented the background, procedures, and software that were developed to evaluate tracking systems. Software has been written to gather resolution and accuracy data for a tracking target's position; while also collecting data regarding the target's orientation resolution and stability. A calibrated linear motion test track is used as a reference in calculating accuracy values. Accuracy data is collected statically at fixed positions along the test track's length and dynamically during track stage movement. The dynamic lag of a tracker is calculated using dynamic accuracy error data. In the appendices, the tracker test software is discussed in overview form, a sample test plan is provided, and sample test program output is shown.

During the process of developing the tracking test system, where several tracking systems were used to validate the test methods, the following conclusions are noted:

- While the tracker test program was written to be generic, each tracker requires a separate software driver due to the differences in tracker features, data formats, and interface protocols.
- The test equipment is capable of measuring tracking systems with position errors that approach 0.1 mm.
- During target motion, dynamic accuracy errors include static accuracy errors. This can make dynamic errors appear larger or smaller than the static error indicated after the motion stops.
- To measure a tracking system's dynamic lag by using dynamic position accuracy data, static position accuracy errors must be removed from dynamic position accuracy errors.
- Variations in dynamic data lag will occur when the tracker data transfer is not synchronized to the tracker update rate. The maximum additional lag is equal to the update rate.

The integration of the test procedures, track equipment, and software discussed in this report is one step in evaluating a tracking system for use in weapon firing simulations. Before this step can have any meaning, the requirements for the weapons firing simulation task must be defined. Once these are defined, a complete evaluation of a candidate tracking system must be performed to make a comparison between the tracker and the task, or between several trackers and the task.

Recommendation is made to investigate adding an orientation reference to the test equipment. While the test procedures and equipment discussed in this report provide a relative target position accuracy reference, no reference is provided for angular orientation accuracy. If a complete analysis of a 6DOF tracking system is to be performed, an orientation reference needs to be included in the test procedures. Orientation analysis is limited to stability of the output data. The addition of orientation reference equipment and procedures to the test suite is not trivial, requiring additional rotational motors and encoders to be mounted on top of the translational stage. The weight of the additional orientation motors may require a new linear motion track to handle the additional weight. A new test plan that includes programmed orientation changes during position movements must be developed. This new orientation data must then be tabulated and graphed to interpret the data.

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APPENDIX A AWST TRACKER TEST SOFTWARE OVERVIEW

INTRODUCTION

The AWST tracker test program was written for Windows95 using Microsoft Visual C V5.0. Software libraries from Aerotech were used to control and communicate with the Unidex-500 servo controller that controls the motion table. Software libraries from National Instruments were used to control and communicate with the PC-TIO-10 timer/input/output card, which is used to implement a hardware clock. The standard Win32 Comm Port Application Programmer Interface (API) calls were used to setup, control, and communicate with the serial ports.

A set of standardized tests can be run on each tracker. This was accomplished by using indirect calls to tracker-specific algorithms within the test code. Each tracker has a driver module that implements these calls. A new driver module must be written for each tracker to be tested. A standard set of data was taken for each test, statistically analyzed, and the results stored to disk.

STARTING THE PROGRAM

The name of the executable program is “Tracker Test Version 1.exe”. The tracker test program can be run by double-clicking on it from Windows Explorer. When the program is started it displays the screen shown in Figure A-1. As can be seen from the title bar, no tracker is selected for test when the program loads.

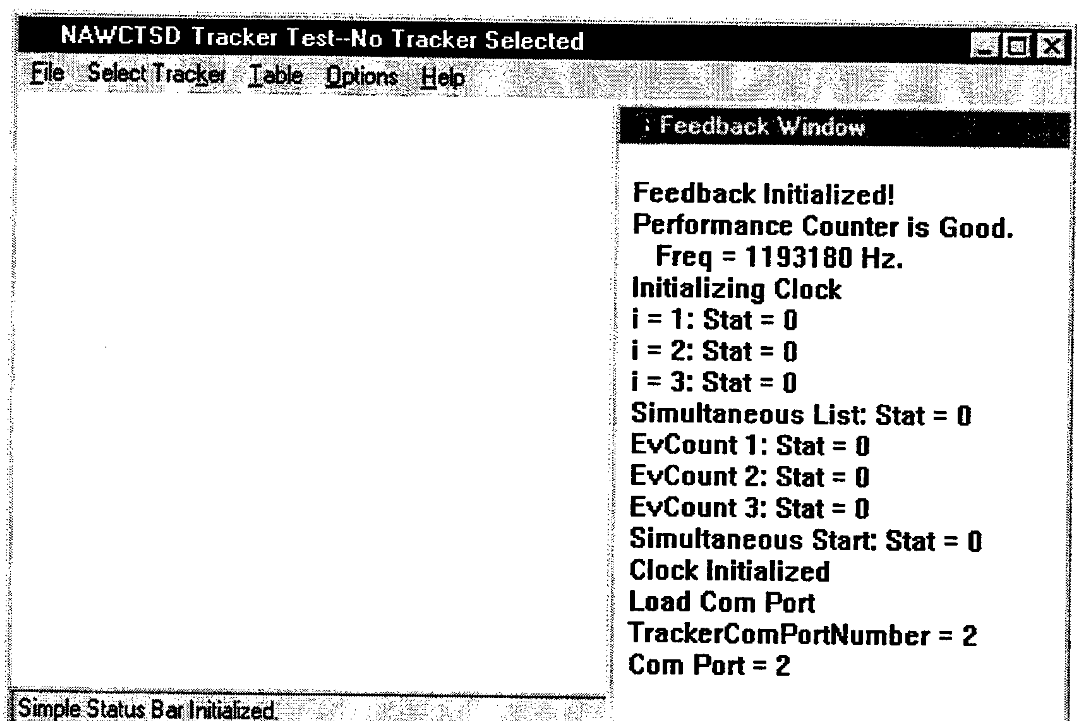

Figure A-1. Tracker Test Program Opening Menu Window.

Main Menu

The main menu bar contains selections for File, Select Tracker, Table, Options, and Help. Each of these will be described below.

__File__ has two selections:

Test Clock.	Tests the real time clock.
Exit.	Exits the program.

__Select Tracker__ currently has four selections:

None.	No tracker is selected. This is the initial condition.
Vscope.	Selects the Vscope tracker for testing.
IST.	Selects the Infrared Spot Tracker for testing
IS-600.	Selects the InterSense IS-600 tracker for testing.

__Table__ allows the Aerotech motion table to be tested independently of the trackers. It has four selections:

Check Status.	Checks the status of the servo controller and motion table.
Send Table Home.	Returns the table to its "Home" position.
Test Motion English.	Uses English units to test motion (inches).
Test Motion Metric.	Uses Metric units to test motion (mm).

__Options__ contains selections for miscellaneous items. In the initial menu it has two selections.

Feedback Window [On/Off].	Turns display of the feedback window on and off (On is checked).
Set Tracker Serial Port.	Selects the serial port the tracker is attached to.

__Help__ contains two selections:

Help.	Help has not been implemented but opens up a dialog box to say that it has not been implemented.
About.	About opens up a dialog box that identifies the program and the AWST project.

SELECTING A TRACKER

When a tracker is selected the menu bar changes to reflect the choices that are available for testing that particular tracker. The title bar changes to identify the tracker that has been selected. The status bar at the bottom of the screen also changes to display various parameters of interest for the selected tracker. Figure A-2 shows the menu for the Infrared Spot Tracker and Figure A-3 shows the menu for the InterSense IS-600 tracker.

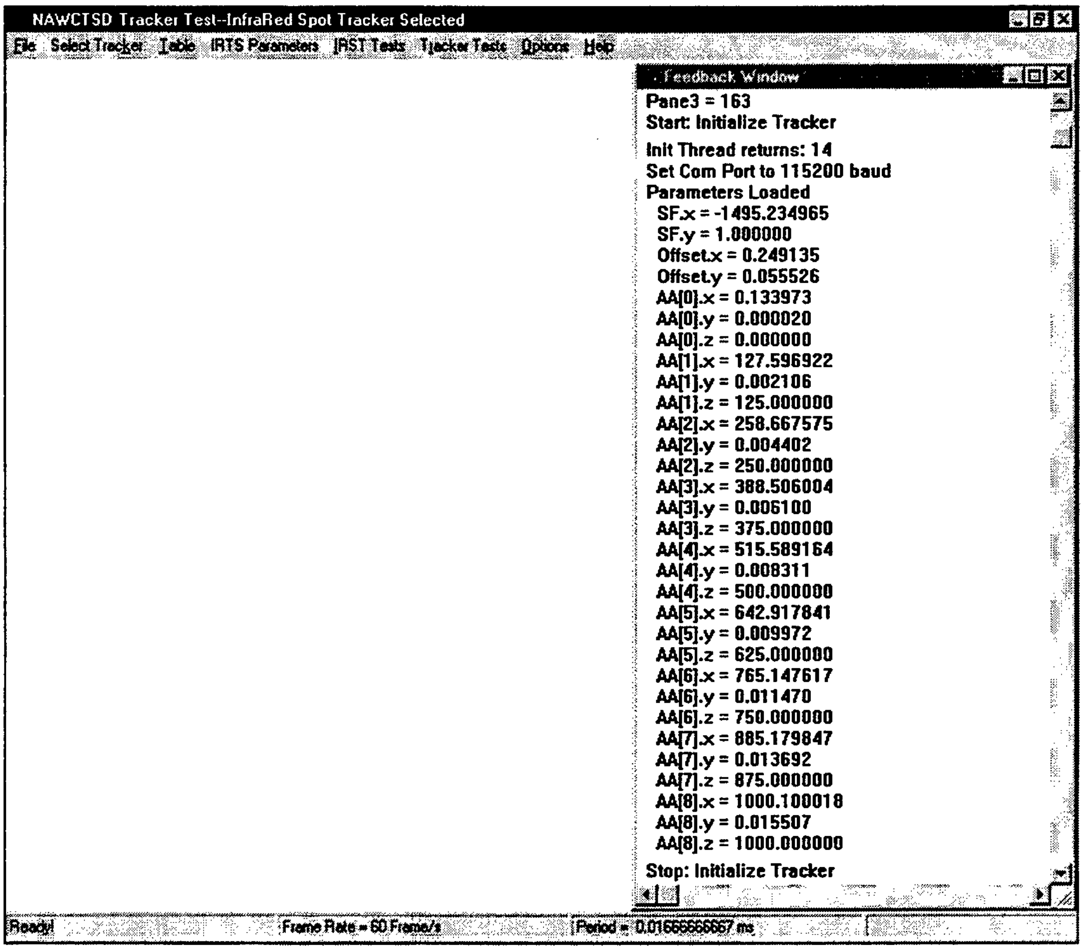

Figure A-2. IST Tracker Test Menu.

These figures are representative, not inclusive, of the trackers that can be tested. Note that when a tracker is selected, the Options menu changes. The selection for setting the serial port goes away once a tracker has been selected. The program does not allow the serial port to be changed once a tracker is selected. The "Set Tracker Serial Port" selection is replaced by the selection "Set Motor Rate". The motor rate selection allows the speed at which the table is moved in several of the selections in the "Tracker Tests" menu to be changed.

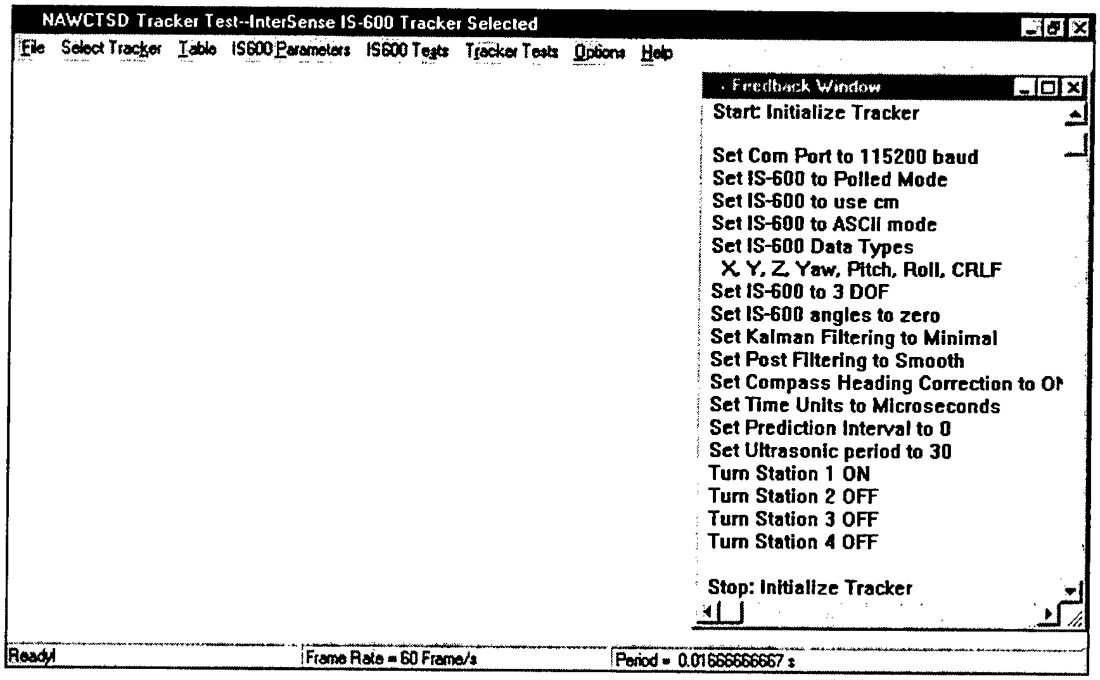

Figure A-3. InterSense IS-600 Tracker Menu.

Note also that several new menu items have been added. These will vary depending on which tracker is selected. The "Tracker Tests" menu item will always appear when a tracker is selected. This menu selects the general tests that are run on each tracker. In addition, one or more menu items specific to the selected tracker will appear. These allow for the setting of various parameters and the running of tests specific to that tracker.

GENERAL TRACKER MENU

Since the "Tracker Tests" menu item appears whenever a tracker is selected, it will be described first. The selections under "Tracker Tests" are described below. Note that the first alignment routine [Align Table (Mechanical)] does not store any data. The second alignment routine [Align Coordinate System (SW)] stores the alignment parameters, the data used to calculate them, and some of the intermediate results in an ASCII text file with a name picked by the user and a filetype of ".txt". The four test routines all use the same data storage method, described next. The raw data from each test is stored in ASCII form in a user named file with a filetype of ".txt". Statistical position data is stored in a file with the same name as the raw data but with a filetype of ".pos.dat" and rotational statistics are stored in a file with a filetype of ".rot.dat". All these files are stored as tab delimited ASCII text to facilitate importation into spreadsheets such as Excel.

<u>Tracker Test Menu</u> has six selections:

Align Table (Mechanical).	This invokes a routine that helps to mechanically align the Aerotech table relative to the tracker to be tested.
Align Coordinate System (SW).	This invokes a routine that positions the table near both ends of its travel in sequence, takes data from the tracker and calculates an offset and a set of 3D rotation angles to precisely align y-axis of the tracker to the tables linear axis.
Resolution Test.	This invokes a routine that takes individual 100 sample data sets and calculates statistics for them. This data is stored to disk.
Cumulative Resolution Test.	This invokes a routine that takes individual 100 sample data sets and calculates statistics for each data set and for a collection of data sets. This data is stored to disk.
Static Accuracy Test.	This invokes a routine that takes n samples at user defined intervals of k mm from the selected starting point to the selected ending point. The starting point and ending point must be between 0 and 1100 mm and should not be the same. The start point defaults to 0 mm, the end point defaults to 1000 mm, n defaults to 20, and k defaults to 100. Statistical calculations are done on this data. The data and statistics are stored to disk.
Dynamic Accuracy Test.	This invokes a routine that takes 100 data points at the "Home" position of the track, moves the table while taking data to the end of the track, and takes 100 more data points at the end. This data is stored to disk.

TRACKER SPECIFIC MENU SELECTIONS

This section will describe the menu items that are specific to individual trackers.

The selection of the Vscope tracker adds two pull-down menu selections to the top-level menu. They are "Vscope Parameters" and "Vscope Tests".

<u>Vscope Parameters</u> contains four selections: Select Target(s), Select Data Rate, Select Vscope Mode, and Select Baud Rate. Each of these selections is briefly described below.

Select Target(s).	This selection opens up a dialog box that allows the user to select one or more (up to three) of the eight available targets to be tracked.
Select Data Rate.	This selection opens up a dialog box that allows the user to select the data rate (actually the period in milliseconds) at which the Vscope takes data.
Select Vscope Mode.	This selection opens up a dialog box that allows the user to select the Vscope operating mode. The choices are Raw Data Mode, which gives the distances from each tracking tower to each target; and Cartesian Mode, in which the Vscope calculates the Cartesian (3D) coordinates for each target relative to origin of the Vscope array.
Select Baud Rate.	This selection opens up a dialog box that allows the user to select the Baud rate at which the Vscope communicates with the computer.

<u>Vscope Tests</u> contains three selections: Test Vscope, Display Data, and File Vscope Data. Each of these selections is briefly described below.

Test Vscope.	This selection sends a simple query to check whether or not the Vscope is ready. It displays the results in the "Feedback Window".
Display Data.	This selection opens up a dialog box that continuously displays Vscope data until exited.
File Vscope Data.	This selection captures a set of Vscope data and writes it to a user-selected file.

The IST also adds two pull-down menu selections to the top-level menu. They are "IST Parameters" and "IST Tests".

IST Parameters contains three selections: Frame Rate, Use Fine Data, and Use PSD Data. Each of these selections is briefly described below:

Frame Rate.	This selection is currently not implemented. The frame rate is fixed at 60 Hz.
Use Fine Data.	This selection is either On or Off. If it is checked, the program will calculate linearity corrections using an algorithm similar to the one used in an actual simulator that employs the IST tracker. If it is unchecked, the program will use the data from the IST tracker uncorrected.
Use PSD Data.	This selection is either On or Off. If it is checked, the program will expect the IST tracker to send raw PSD values. This is the normal operating mode of the IST. The IST tracker can also calculate screen coordinates and transmit them. If this selection is unchecked, the program will expect the IST tracker to send screen coordinates.

IST Tests contains seven selections: Tracker On, Tracker Off, Calc. Alignment Params, Track Spot Raw, Track Spot Coarse, Track Spot Fine, and Save Data to File. Each of these selections is briefly described below:

Tracker On.	This selection is currently not implemented.
Tracker Off.	This selection is currently not implemented
Calc. Alignment Params.	This selection runs a routine to calculate the fine alignment parameters needed to correct for non-linearity.
Track Spot Raw.	This selection opens up a dialog box that continuously displays the raw PSD values from the tracker until exited.
Track Spot Coarse.	This selection opens up a dialog box that continuously displays the Coarse values from the tracker until exited. Coarse values are scaled to millimeters to align with the motion table, but are not corrected for non-linearity.

Track Spot Fine.	This selection opens up a dialog box that continuously displays the Fine values from the tracker until exited. Fine values are scaled to millimeters to align with the motion table, and corrected for non-linearity. If fine alignment data has not been calculated, the data will be output using coarse alignment.
Save Data to File.	This selection captures a set of IST data and writes it to a user-selected file.

The IS-600 also adds two pull-down menu selections to the top-level menu. They are "IS600 Parameters" and "IS600 Tests".

IS600 Parameters contains five selections: Frame Rate, Set Parameters, Set Ultrasonic Period, Transmit Mode Polled, and Ignore Frame Rate. Each of these selections is briefly described below:

Frame Rate.	This selection opens up a dialog box to allow the user to select a frame rate for taking data in polled mode.
Set Parameters.	This selection opens up a dialog box that allows the user to set various IS-600 parameters. These include Kalman Filtering Mode, Post Filtering Mode, Compass Heading Correction, Prediction Interval, Time Units for Prediction Interval, and Transmit Data Mode (ASCII or Binary).
Set Ultrasonic Period.	This selection opens up a dialog box that allows the user to select the period between samples in the ultrasonic subsystem of the IS-600.
Transmit Mode Polled.	This selection is either On or Off. If it is checked, the program obtains data from the IS-600 in polled mode. If it is unchecked, the IS-600 sends data continuously and the program attempts to capture data without loss.
Ignore Frame Rate.	This selection is either On or Off. If it is checked, the program polls the IS-600 as fast as it can. If it is unchecked, the program generates an internal frame rate as set in the first item in this menu, and polls the IS-600 once per frame.

IS600 Tests contains five selections: Display System Parameters, Test IS600, Display Data, File IS600 Data, and IS-600 Dynamic Test. Each of these selections is briefly described below:

Display System Parameters.	This selection queries the IS-600 for its current parameters and displays them (and a few internal parameters) in a dialog box.
Test IS600.	This selection checks the IS-600 for proper operation.
Display Data.	This selection opens up a dialog box that displays tracking data continuously until exited.
File IS600 Data.	This selection captures a set of IS-600 data and writes it to a user-selected file.
IS-600 Dynamic Test.	This selection runs a specially tuned version of the Dynamic Accuracy Test from the "Tracker Tests" menu. This special version is optimized to obtain the best possible speed with the IS-600.

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APPENDIX B SAMPLE TRACKING SYSTEM TEST PLAN

The following is a file note that was written to outline the steps for testing a tracking system using the AWST Tracker Test Program.

1. This test plan details the tracking system settings and target/track positions that will be in effect during data gathering activities. There are three basic types of data to be gathered, Resolution, Static Accuracy, and Dynamic Accuracy. All three of these data sets should be captured to form a complete tracker test set. Data gathering activities are performed through use of the NAWCTSD WIN95 software, AWST Tracker Test program. Filename schemes for each test's output are suggested, filetypes are automatically appended for data categories of raw data and position and orientation statistics. Complete tracker test sets should be stored in a separate WIN95 folder with a name that indicates the date and any particulars concerning the test setup. To reduce Win95 processor interrupts when running the tracker test software make sure that the Win95 screensaver and CDROM auto-insert feature are disabled.

2. All positions specified in this test plan are in tracker system coordinates and in units of millimeters. Physical positioning of the tracker target should be within a few millimeters of the specified positions. Check the target positions for each test to insure a clear line-of-sight between the target and sensor when required by the tracking system.

3. Data gathered should be the complete 6DOF data (x, y, z, yaw, pitch, roll) if available from the tracker system, otherwise 3DOF (x, y, z) or 2DOF (x, y).

4. <u>Resolution Data Tests</u> - Resolution data should be collected at four points within the tracker motion box. Figure B-1 is a plan view looking down on the tracking system and its motion box using the InterSense IS-600 as an example. These points are located at the following coordinates:

1) - (0, y, 1000)
2) - (0, y, 2000)
3) - (-1000, y, 1000)
4) - (1000, y, 1000)

These coordinates follow the axes labeled in the plan view of Figure B-1, where Z extends out from the sensor(s), X is horizontal across the sensor(s) and Y (not indicated) is vertical. Y coordinates should be set approximately through the vertical middle of the motion box. Note that positions 1 and 2 fall on the major axis of the tracking system at one and two meters. If positions 2, 3, or 4 fall outside the motion box of a particular tracking system, they may be brought in toward position 1 until they are within the motion box. For reference purposes with other tracking systems, position 1 should always be 1 meter from the tracking system origin along the major axis.

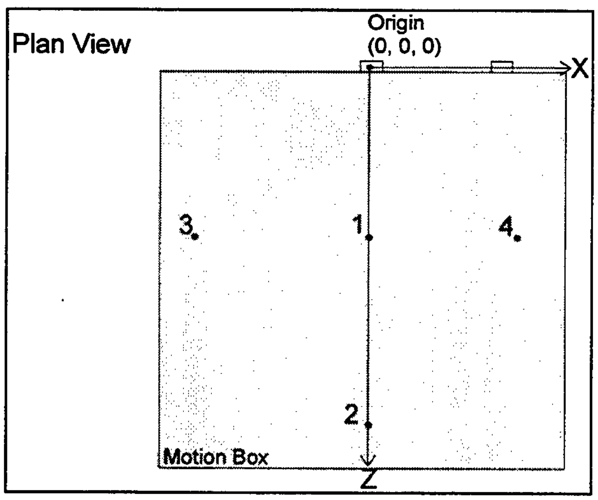

Figure B-1. Resolution Data Positions.

For tracking systems that provide 2D aimpoint data, the resolution test positions would be limited to a plane parallel to the display screen. This plane would be located at the distance D_{2D} as shown in Figure 2.

Tracking Test Settings for Resolution Data

a - All resolution data to be taken with noise filtering and correction options turned off.
b - Where possible, data will be read in a polled manner at a rate of at least 30 Hertz.
c - Data output should be in the tracking coordinate system format.
d - Three Resolution Data Sets (100 samples) will be taken at each position, each set's statistics calculated, and then each position's mean statistics will be calculated.
e - Filename Scheme: *"Tracker Name"+Res+"Pos#"* (i.e., IS600 Res 1)
f - Retest Point 1 with track movement to check for track induced artifacts, append TM to filename

5. Static Data Tests - Static data involves use of the U500 track. The track must be positioned, the target mounted to the target tower, and physical/mathematical alignment procedures performed. Positioning of the track is shown in Figure B-2, where the track is arranged to provide the following: 1) target motion across the sensor array (or horizontally across the motion box) or 2) target motion in and out of the motion box along the major axis of the tracking system. For 2DOF systems, the second track arrangement is impractical and only the horizontal target motion is required. Some tracking systems may only allow the targets to fall within certain areas of its coordinate system (such as the 1st or positive quadrant); for those cases center the track within the motion box. Figure B2 shows the two arrangements of the track within the motion box and the approximate coordinates of the track home and end positions for each track positioning. These home and end coordinates (in the tracking coordinate system format) are as follows:

1_h - (0, Y, 1000)
1_e - (1000, Y, 1000)
2_h - (0, Y, 1500)
2_e - (0, Y, 500)

where 1_h is the home position and 1_e is the end position for track position 1; 2_h and 2_e are for track position 2. The Y coordinate value is a function of the combined track and tower height, and arrangements should be made to have the target positioned near the vertical center of the motion box.

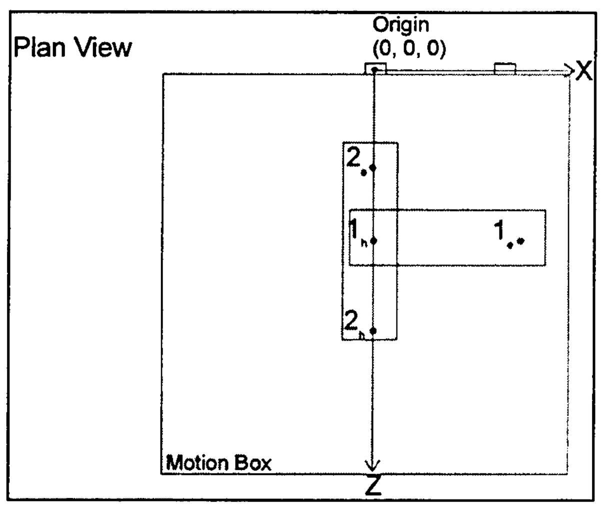

Figure B-2. Track Positions for Static Tests.

Once the alignments are performed, the static tests will be performed by moving from the track home to end position (1000 mm) in ten steps of 100mm. The tracker test software will take 20 samples at each of the eleven positions and calculate the statistics.

Tracker Test Settings for Static Data

a - Where possible, data will be read in a polled manner at a rate of at least 30Hertz.
b - Perform a physical track alignment for each position, followed by a mathematical alignment. During mathematical alignment, the tracker should have filtering and correction options turned off. Save the mathematical alignment with a filename scheme of: *"Tracker Name"+Static Align+ "Pos#"* (i.e., IS600 Static Align1).
c - Data output from static tests should be in the track coordinate system format.
d - For each position of the track, static data runs will be made with available filtering off and on. Any other pertinent settings should also be toggled (ex. for IS-600 compass correction on/off, CC1/CC0).
e - To speed data gathering, the dynamic tests for each static run/track position should immediately follow the static tests. This will allow the track position alignment and static data to apply to the dynamic tests.
f - Filename Scheme: *"Tracker Name"+Static+"Pos#"+"Filter Mode"+"Other Toggle Setting(s) ···"*. For a complete set of IS-600 static tests with Jump&Smooth filter modes and CC1/CC0 compass settings there would be eight files with filenames of:

IS600 Static 1 Jmp CC0	IS600 Static 2 Jmp CC0
IS600 Static 1 Jmp CC1	IS600 Static 2 Jmp CC1
IS600 Static 1 Sm CC1	IS600 Static 2 Sm CC1
IS600 Static 1 Sm CC0	IS600 Static 2 Sm CC0

6. Dynamic Data Tests - Dynamic data gathering is performed using the same track and target positioning of the static tests. After performing the static tests for each filter/option permutation of position 1, the dynamic tests for that same filter/option setting and position will be performed. After all static and dynamic tests for position 1 are finished, the track will be repositioned for another set of static and dynamic filter/option permutations at position 2. The track and target positions are provided in the static test section and depicted in Figure B-2.

The default track speed of the dynamic tests will be 600 mm/sec. The tracker test program will take the tracker target data in three phases:

Phase I - a set of 100 samples at the home position with the target stationary
Phase II - a variable size set of data taken during the track stage/target movement from the track home to end positions
Phase III - a set of 100 samples at the end position with the target stationary

During these three phases, the tracker test program will continuously collect the target position and orientation, the track position, and the time. These data will be used by the software to calculate dynamic statistics, and also used in an Excel spreadsheet to chart position and orientation errors and to calculate data lag.

Tracker Test Settings for Dynamic Data

a - Data should be read in a manner that allows capture of all tracking system samples without missing any samples. When capture of all samples is not possible, data should be captured at the fastest rate possible. Steps should be taken to ensure that the tracker sample is the most current sample. This may be done by requesting tracker data in a polled manner at the tracking system's update rate, or at slightly higher timings than the AWST tracker test program's minimum cycle time (currently 5 milliseconds). Alternatively, the tracker could be setup to send data continuously with the serial port buffer flushed before each sample reading.

b - The alignment for the track position from the previous static test may be used if the track has not been moved. Otherwise, check the physical track alignment and redo the mathematical alignment. During mathematical alignment, the tracker should have filtering turned off. Save the mathematical alignment with a filename scheme of: *"Tracker Name"+Dyn Align+ "Pos#"* (i.e. IS600 Dyn Align1).

c - Data output from dynamic tests should be in the track aligned coordinate system format.

d - Dynamic data runs will be made for each track position with available filtering off and on. Any other pertinent settings should also be toggled (ex. for IS-600 compass correction on/off, CC1/CC0). After dynamic data has been collected for a filter/option setting of track position 1, return to the static test section and setup the next filter/option permutation. Take the next static and dynamic data and proceed to the next filter/option setting. After all filter/correction permutations of a track position have been gathered, reposition the track according to Figure B-2, and repeat the static and dynamic tests for the various filter and option permutations.

e - Dynamic Filename Scheme: *"Tracker Name"+Dyn+"Pos#"+"Filter Mode"+ "Other Toggle Setting(s) ···"*. For the IS-600 a complete set of dynamic tests with Jump&Smooth filter modes and CC1/CC0 compass correction settings would be eight files with filenames of:

IS600 Dyn 1 Jmp CC1	IS600 Dyn 2 Jmp CC1
IS600 Dyn 1 Jmp CC0	IS600 Dyn 2 Jmp CC0
IS600 Dyn 1 Sm CC1	IS600 Dyn 2 Sm CC1
IS600 Dyn 1 Sm CC0	IS600 Dyn 2 Sm CC0

APPENDIX C SAMPLE TRACKER TEST OUTPUTS

This appendix to the AWST weapons simulation tracking test methods report provides sample outputs from the tracker test program. These samples compliment the discussion of the Tracking Test Procedures contained in the Tracking Test Methods section. The sample outputs consist of data tables and plots of data as described in the Resolution Tests, Static Accuracy Tests, and Dynamic Accuracy Tests sections of the Tracking Test Procedures.

Several tracking systems were used during the course of producing the AWST tracker test program. These tracking systems are: the InterSense IS-600, the NAWCTSD Infrared Spot Tracker (ISD), and the Esched VSCOPE. A short description of each tracking system is provided to provide the reader with background information.

The InterSense IS-600 tracking system is a combination tracking system that uses two tracking technologies to provide 6DOF tracking. In the IS-600 version tested, an ultrasonic transmitter/receiver system is used to determine (x, y, z) position while an inertial system provides (yaw, pitch, roll) orientation angles. The ultrasonic system uses one ultrasonic transmitter that serves as the target and has three ultrasonic receivers that are used in performing 3D position triangulation. The inertial system uses micromachined accelerometers, inclinometers, and a magnetic compass to keep track of a target's orientation. The division between the position and orientation systems leads to each system having its own independent operating parameters (e.g., sample rates, update rates, accuracies, lag, etc.). These two sensor systems have separate targets and produce their outputs independently, with the ultrasonic sampling occurring at a lower rate. The ultrasonic data is buffered, combined with the orientation data, and output as one data record at the inertial update rate. Future IS-600 versions are planned by InterSense to provide intermediate updates of the ultrasonic position data using the inertial data.

The Infrared Spot Tracker (IST) is a 2DOF tracking system that effectively provides a (yaw, pitch) orientation angle set. The system uses a Position Sensing Detector (PSD) to track a near-infrared spot projected onto a display screen from a collimated infrared source mounted on a weapon. Use of the IST involves a calibration procedure to remove non-linearities in the IST lens. The IST provides output that is related to fractional display pixel positions, which are then referenced to a nominal weapon position to determine yaw and pitch angles.

The Esched VSCOPE tracker is an ultrasonic system that provides 3DOF in the form of (x, y, z) position data. The system uses a single ultrasonic transmitter as a target with three ultrasonic receivers performing 3D position triangulation. The InterSense IS-600 tracking system's ultrasonic position tracking subsystem is a repackaged VSCOPE system.

The sample outputs in this appendix are from the InterSense IS-600 tracking system that was used during the concept and development phases of creating the tracking test program. The sample outputs are not intended to be a complete analysis of the tracking systems used and are provided for documentation purposes only.

SAMPLE RESOLUTION OUTPUT

Mean Position Resolution Statistics

Position resolution statistics for the IS-600 tracker are provided in Table C-1. Tracker readings were taken with the ultrasonic target located at (0, 0, 1000) mm (Position 1 as described in Appendix B, Figure B-1) relative to the tracker's default coordinate system. This position is located 1 meter from the IS-600 ultrasonic origin along its z-axis.

Table C-1. Position Resolution Statistics, Position 1 - (0, 0, 1000) mm

Static Resolution Test	
Frame Rate = 30 frames/s	
Sample Period = 0.0333333333 s	Orientation Inertial Mode: ON
Translation Values NOT Calculated	Position Inertial Mode: OFF
Translation Disabled	Time Units: microseconds
InterSense IS-600 Settings	Prediction Interval = 0
Output Format: ASCII	UltraSonicPeriod = 30 ms
Units: cm	Kalman Filtering: minimal
Transmit Mode: polled	Post Filtering: jump
Software ID: 2.0.8	Tilt Compensation: ON
System ID: IS300-PRO	Heading Compensation: OFF
Station 1: ON	Tracking Mode: 6 DOF
Station 2: OFF	Date and time: Wed Jun 03 10:46:43 1998
Station 3: OFF	Motor was OFF
Station 4: OFF	Cumulative Resolution Test

Count	Mean X	Mean Y	Mean Z	Mean R	SD X	SD Y	SD Z	SD R
1	-1.173	-0.105	1000.26	1000.261	0.3061	0.3157	0.2132	0.4887
2	-2.026	-0.745	999.693	999.6953	0.3966	0.304	0.1597	0.5246
3	-0.371	-0.44	1000.394	1000.394	0.2883	0.3651	0.1516	0.4893
Summary Data								
Means								
3	-1.19	-0.43	1000.116	1000.117	0.3303	0.3283	0.1748	**0.5009**
SDs								
3	0.8276	0.3201	0.3721	0.371	0.0581	0.0325	0.0335	**0.0206**

The top part of Table C-1 provides information about the tracking system parameters during the test. These parameters are based on the program menu choices made when setting up the tracker test program.

The next block of data in Table C-1, provided in a row/column format, are the Position Resolution Statistics as defined in Table 2. This block contains the statistical results of three individual instances of running the resolution test, where 100 (x, y, z) data samples were taken each time. The Count column contains the index of each individual resolution test. Note that all data values are in millimeters (mm). The Mean X, Mean Y, and Mean Z columns contain the means (averages) of each of the 100 (x, y, z) data samples for the three resolution tests. Referring to the equations of Table 2, these Mean X, Mean Y, and Mean Z values specify the Position Arithmetic Means of the target based on 100 data samples. The Mean R column contains the means of the calculated tracker origin to target distances. The next three columns contain the standard deviations of the x, y, and z data samples from their means, SD X, SD Y, and SD Z. The last column contains the values for the radial standard deviation, SD R, which are calculated from the x, y, and z standard deviations and are not associated with the calculated Mean R error values. Referring to Table 2, SD X, SD Y, and SD Z are the Position Resolution values for the X, Y, and Z dimensions and SD R is the Radial Resolution value.

The Summary Data section of Table C-1 provides the Mean Position Resolution Statistics as defined in Table 4. These statistics are calculated from the results of the three individual resolution tests. The summary allows a number of 100 data sample runs of the resolution test to be combined. The net result is a data set that describes the resolution over the entire cumulative set of data; 300 data samples in this case. Referring to the equations of Table 4, the summary data values in the Mean X, Mean Y, and Mean Z columns of Table C-1 provide the Average Position Arithmetic Means and the Standard Deviations of the Mean Positions. The summary data values in the SD X, SD Y, and SD Z columns provide the Average Position Resolutions for the X, Y, and Z dimensions and their corresponding Standard Deviations of the Position Resolutions. The summary values in the SD R column provide the Average Radial Position Resolution and the Standard Deviation of the Radial Position Resolutions. These last two summary values provide the overall position resolution of the tracking system, indicating that the tracking system has a Average Radial Position Resolution of 0.5009 mm ± 0.0206 mm under the specified test conditions.

Table C-2 contains statistical values for another position, Position 2, at (0, 0, 2000) mm. This is twice the distance out the z-axis relative to Table C-1. The summary values indicate that for this increased distance, the tracking system has an Average Radial Position Resolution of 1.311 mm ± 0.2778 mm. Relative to Position 1, Position 2 has a lower average resolution by a factor of over 2.5 with a standard deviation that is 10 times larger.

Table C-2. Position Resolution Statistics, Position 2 - (0, 0, 2000) mm

Static Resolution Test
Frame Rate = 30 frames/s
Sample Period = 0.0333333333 s
Translation Values NOT Calculated
Translation Disabled
InterSense IS-600 Settings
Output Format: ASCII
Units: cm
Transmit Mode: polled
Software ID: 2.0.8
System ID: IS300-PRO
Station 1: ON
Station 2: OFF
Station 3: OFF
Station 4: OFF

Orientation Inertial Mode: ON
Position Inertial Mode: OFF
Time Units: microseconds
Prediction Interval = 0
UltraSonicPeriod = 30 ms
Kalman Filtering: minimal
Post Filtering: jump
Tilt Compensation: ON
Heading Compensation: OFF
Tracking Mode: 6 DOF
Date and time: Wed Jun 03 11:06:55 1998
Motor was OFF
Cumulative Resolution Test

Count	Mean X	Mean Y	Mean Z	Mean R	SD X	SD Y	SD Z	SD R
1	-1.086	-0.541	2002.152	2002.152	1.0263	0.6978	0.3246	1.2828
2	2.074	2.892	2004.014	2004.017	1.1928	1.0219	0.315	1.6019
3	1.451	2.214	2003.957	2003.959	0.8591	0.5691	0.1929	1.0484
Summary Data								
Means								
3	0.813	1.5217	2003.374	2003.376	1.0261	0.7629	0.2775	**1.311**
SDs								
3	1.6738	1.8182	1.059	1.0602	0.1668	0.2333	0.0734	**0.2778**

Mean Orientation Resolution Statistics

When testing a 6DOF tracker, orientation resolution data is recorded along with the position resolution data. This data is used to calculate statistics for evaluating orientation resolution.

Orientation resolution statistics for the IS-600 tracker target at Position 1 are provided in Table C-3. This data was taken at the same time as the position data for Table C-1.

Table C-3. Orientation Resolution Statistics, Position 1 - (0, 0, 1000) mm

Static Resolution Test
Frame Rate = 30 frames/s
Sample Period = 0.0333333333 s
Translation Values NOT Calculated
Translation Disabled
InterSense IS-600 Settings
Output Format: ASCII
Units: cm
Transmit Mode: polled
Software ID: 2.0.8
System ID: IS300-PRO
Station 1: ON
Station 2: OFF
Station 3: OFF
Station 4: OFF

Orientation Inertial Mode: ON
Position Inertial Mode: OFF
Time Units: microseconds
Prediction Interval = 0
UltraSonicPeriod = 30 ms
Kalman Filtering: minimal
Post Filtering: jump
Tilt Compensation: ON
Heading Compensation: OFF
Tracking Mode: 6 DOF
Date and time: Wed Jun 03 10:46:43 1998
Motor was OFF
Cumulative Resolution Test

Count	Mean Yaw	Mean Pitch	Mean Roll	SD Yaw	SD Pitch	SD Roll	SD C
1	-13.91	0.3468	0.1948	0	0.0145	0.025	0.0145
2	-13.91	0.3247	0.1845	0	0.0115	0.0255	0.0115
3	-13.91	0.3224	0.2273	0	0.0185	0.0177	0.0185
Summary Data							
Means							
3	-13.91	0.3313	0.2022	0	0.0148	0.0228	**0.0148**
SDs							
3	0	0.0135	0.0223	0	0.0035	0.0043	**0.0035**

Table C-3 provides three sets of Orientation Resolution Statistics as defined in Table 3. Note that all orientation data values are in degrees. These three sets are in the first block of data that is provided in a row/column format. These are the statistical results of three individual instances of running the resolution test, where 100 (yaw, pitch, roll) data samples were taken each time. The Count column contains the index of each individual resolution test. The Mean Yaw, Mean Pitch, and Mean Roll columns contain the means (averages) of the 100 (yaw, pitch, roll) data samples for each of the three resolution tests. Referring to the equations of Table 3, these Mean Yaw, Mean Pitch, and Mean Roll values specify the Orientation Arithmetic Means of the target based on 100 data samples. The next three columns contain the standard deviations, SD Yaw, SD Pitch, and SD Roll, of the yaw, pitch, and roll data samples from their means. These standard deviation values are the Orientation Resolution values of Table 3. The last column contains the values for the Conic Resolution, SD C, which are calculated from the SD Yaw and SD Pitch values.

The Summary Data section of Table C-3 provides the Mean Orientation Resolution Statistics of Table 5. These statistics are calculated from the results of the three individual orientation resolution tests. The tracker test software allows a number of 100 data sample runs of the resolution test to be combined in this summary. The net result is a data set that describes the orientation resolution over the entire cumulative set of data. Referring to Table 5, the summary values in the Yaw, Pitch, and Roll columns provide the Average Orientation Arithmetic Means and the Standard Deviations of the Mean Orientations. The summary values in the SD Yaw, SD Pitch, and SD Roll columns provide the yaw, pitch, and roll angle Average Orientation Resolutions and their corresponding Standard Deviations of the Orientation Resolutions as defined in Table 5. The summary values in the SD C column provide the Average Conic Resolution and the Standard Deviation of the Conic Resolution.

These last two summary values provide the overall orientation resolution of the tracking system, indicating that the tracking system has an Average Conic Resolution of 0.0148 degrees ± 0.0035 degrees under the specified test conditions.

Orientation resolution statistics for the IS-600 tracker at Position 2 are provided in Table C-4. This data was taken at the same time as the position data for Table C-2. The Average Conic Resolution presented in Table C-4 is 0.0188 degrees ± 0.0031 degrees. Because the IS-600 orientation sensor (inertial) is sourceless, changes in position alone should not affect its operation. This is reflected by the minor change in the Conic Resolution values between Position 1 (Table C-3) and Position 2 (Table C-4).

Table C-4. Orientation Resolution Statistics, Position 2 - (0, 0, 2000) mm

Static Resolution Test
Frame Rate = 30 frames/s
Sample Period = 0.0333333333 s
Translation Values NOT Calculated
Translation Disabled
InterSense IS-600 Settings
Output Format: ASCII
Units: cm
Transmit Mode: polled
Software ID: 2.0.8
System ID: IS300-PRO
Station 1: ON
Station 2: OFF
Station 3: OFF
Station 4: OFF

Orientation Inertial Mode: ON
Position Inertial Mode: OFF
Time Units: microseconds
Prediction Interval = 0
UltraSonicPeriod = 30 ms
Kalman Filtering: minimal
Post Filtering: jump
Tilt Compensation: ON
Heading Compensation: OFF
Tracking Mode: 6 DOF
Date and time: Wed Jun 03 11:06:55 1998
Motor was OFF
Cumulative Resolution Test

Count	Mean Yaw	Mean Pitch	Mean Roll	SD Yaw	SD Pitch	SD Roll	SD C
1	-15.9	0.5611	-0.1763	0	0.0205	0.0217	0.0205
2	-15.9	0.574	-0.1963	0	0.0206	0.014	0.0206
3	-15.9	0.5567	-0.1723	0	0.0152	0.0215	0.0152
Summary Data							
Means							
3	-15.9	0.5639	-0.1816	0	0.0188	0.0191	**0.0188**
SDs							
3	0	0.009	0.0129	0	0.0031	0.0044	**0.0031**

Resolution versus Track Operation

To check the effect of the track system on the position and orientation resolution of the tracker, the following tables for the position and orientation resolution statistics with the target at Position 1 are provided. Table C-5 shows the Position Resolution Statistics with the track moving and Table C-6 shows the Orientation Resolution Statistics with the track moving.

Table C-5. Position Resolution Statistics, Track Moving, Position 1

Static Resolution Test	
Frame Rate = 30 frames/s	Orientation Inertial Mode: ON
Sample Period = 0.0333333333 s	Position Inertial Mode: OFF
Translation Values NOT Calculated	Time Units: microseconds
Translation Disabled	Prediction Interval = 0
InterSense IS-600 Settings	UltraSonicPeriod = 30 ms
Output Format: ASCII	Kalman Filtering: minimal
Units: cm	Post Filtering: jump
Transmit Mode: polled	Tilt Compensation: OFF
Software ID: 2.0.8	Heading Compensation: OFF
System ID: IS300-PRO	Tracking Mode: 6 DOF
Station 1: ON	Date and time: Wed Jun 03 10:49:20 1998
Station 2: OFF	**Motor was ON**
Station 3: OFF	**Motor was run during data taking**
Station 4: OFF	Cumulative Resolution Test

Cnt	Mean X	Mean Y	Mean Z	Mean R	SD X	SD Y	SD Z	SD R
1	0.124	-0.377	1000.311	1000.311	0.4654	0.4037	0.3084	0.689
2	-1.131	0.39	1000.182	1000.183	0.4713	0.4663	0.3543	0.7518
3	-0.292	0.036	1000.412	1000.412	0.4874	0.4469	0.3465	0.7465
Summary Data								
Means								
3	-0.433	0.0163	1000.302	1000.302	0.4747	0.439	0.3364	**0.7291**
SDs								
3	0.6393	0.3839	0.1153	0.115	0.0114	0.032	0.0245	**0.0348**

Table C-6. Orientation Resolution Statistics, Track Moving, Position 1

Static Resolution Test	
Frame Rate = 30 frames/s	Orientation Inertial Mode: ON
Sample Period = 0.0333333333 s	Position Inertial Mode: OFF
Translation Values NOT Calculated	Time Units: microseconds
Translation Disabled	Prediction Interval = 0
InterSense IS-600 Settings	UltraSonicPeriod = 30 ms
Output Format: ASCII	Kalman Filtering: minimal
Units: cm	Post Filtering: jump
Transmit Mode: polled	Tilt Compensation: OFF
Software ID: 2.0.8	Heading Compensation: OFF
System ID: IS300-PRO	Tracking Mode: 6 DOF
Station 1: ON	Date and time: Wed Jun 03 10:49:20 1998
Station 2: OFF	**Motor was ON**
Station 3: OFF	**Motor was run during data taking**
Station 4: OFF	Cumulative Resolution Test

Cnt	Mean Yaw	Mean Pitch	Mean Roll	SD Yaw	SD Pitch	SD Roll	SD C
1	-13.91	0.0443	0.0907	0	0.0322	0.0244	0.0322
2	-13.91	0.0636	0.1064	0	0.0159	0.0203	0.0159
3	-13.91	0.0372	0.0631	0	0.0185	0.0237	0.0185
Summary Data							
Means							
3	-13.91	0.0484	0.0867	0	0.0222	0.0228	**0.0222**
SDs							
3	0	0.0137	0.0219	0	0.0088	0.0022	**0.0088**

Table C-5 repeats the position resolution conditions of Table C-1 with the addition of track movement. The track movement has caused the Average Radial Resolution value to increase to 0.7291 mm from the 0.5009 mm value obtained with the track powered down, an increase of 45%. This Average Radial Resolution value indicates that when the target is being tracked during the U500 track movement, the IS-600 tracking system must indicate a radial movement of 0.7291 mm between target samples before a new target position has been resolved. The U500 track motion has added approximately 0.2 mm of noise to the IS-600 tracker position output.

Table C-6 repeats the orientation resolution conditions of Table C-3 with the addition of track movement. The Average Conic Resolution value has increased to 0.0222 degrees with the U500 Track moving compared to 0.0148 degrees with the track powered down, an increase of 50%. Examining the individual orientation angle resolution values reveals that only the Average Pitch Resolution value increased, with the yaw and roll values remaining the same. It appears that the pitch resolution was affected by the track movement. However, examination of the 95% confidence intervals for the averaged conic resolution values with and without the track moving reveals that the track moving value falls within the confidence interval for the case where the track is powered off. The conclusion is that for this specific test the track motion does not affect the orientation data shown in Tables C-3 and C-6.

SAMPLE STATIC ACCURACY TEST OUTPUT

Static Position Accuracy Statistics (Static_Test_Name.pos.std)

Table C-7 is a tracker test program output sample for a static position accuracy test. This output is stored in a file with a filetype of ".pos.std." The table contains information on the tracking system test parameters, statistical static position accuracy summary, and position statistics calculated at each of the static positions of the target.

Table C-7. Static Position Accuracy Statistics for Track Position 1

Incremental Test Data	Station 1: ON
Motor Rate = 600.00	Station 2: OFF
Averaged Data	Station 3: OFF
Date and time: Wed Jun 03 11:52:06 1998	Station 4: OFF
Frame Rate = 30 frames/s	Orientation Inertial Mode: ON
Sample Period = 0.0333333333 s	Position Inertial Mode: OFF
Translation Values Calculated	Time Units: microseconds
Translation Enabled	Prediction Interval = 0
InterSense IS-600 Settings	UltraSonicPeriod = 30 ms
Output Format: ASCII	Kalman Filtering: minimal
Units: cm	Post Filtering: jump
Transmit Mode: polled	Tilt Compensation: OFF
Software ID: 2.0.8	Heading Compensation: OFF
System ID: IS300-PRO	Tracking Mode: 6 DOF

Static Position Accuracy

Target 1

Mean X:	-0.448	SD X:	0.814
Mean Y:	16.036	SD Y:	9.673
Mean Z:	2.175	SD Z:	1.188
Radial Error	16.189	RadialSD:	9.779

Encoder	Target	X1	Y1	Z1	EX1	EY1	EZ1
0	1	-0.60109	0.85779	0.19687	-0.60109	0.85779	0.19687
100	1	-0.03927	105.1666	1.72283	-0.03927	5.1666	1.72283
200	1	-0.17831	207.0985	2.72427	-0.17831	7.09848	2.72427
300	1	-1.58737	310.1261	2.94047	-1.58737	10.12607	2.94047
400	1	1.00885	412.1103	3.28186	1.00885	12.11032	3.28186
500	1	-1.32424	516.4471	3.7878	-1.32424	16.44714	3.7878
600	1	-0.73644	619.8754	2.96395	-0.73644	19.87537	2.96395
700	1	-1.60683	722.6104	2.57535	-1.60683	22.61041	2.57535
800	1	-0.04429	824.8843	2.13159	-0.04429	24.88428	2.13159
900	1	0.12319	927.1494	1.39798	0.12319	27.14935	1.39798
1000	1	0.05366	1030.071	0.20423	0.05366	30.07056	0.20423

Table C-7 contains the static position accuracy output for the IS-600 tracker with the track positioned in the tracker motion box at track position 1 (shown in Appendix B, Figure B-2). In this test, the target was attached to the motion track and moved in 100 mm increments along the track length. At each of the target/track positions, 100 target (x, y, z) data samples were taken along with 100 track encoder samples. These 100 data sample sets for each position were used to perform static position accuracy calculations via the equations of Table 6.

The lower row/column data of Table C-7 contains the Static Position Means and Static Position Errors for the static accuracy test along with the corresponding track encoder positions. The Static Position Means have column headers of X1, Y1, and Z1. The Static Position Errors have column headers of EX1, EY1, and EZ1. The errors listed in the EY1 column correspond to errors along the track motion axis. The errors in the EY1 column indicate that the static position error builds as the target is moved from the track "home" position to the "end" position. At a relative target motion of 1000 mm, the error in target position is 30.07 mm. This value indicates that the tracking system has calculated the target motion to be 30.07 mm more than the 1000 mm track motion.

The Static Position Means and Static Position Errors are averaged over the length of the track movement to provide the Mean Static Position Errors and the Static Position Standard Deviation values. These values are listed in Table C-7 under the heading of Static Position Accuracy, where the Mean X, Mean Y, and Mean Z labels refer to the Mean Static Position Errors and the SD X, SD Y, SD Z, refer to the Static Position Standard Deviations.

With the tracker coordinate system's y-axis aligned to the U500 track, the Mean Y value indicates the averaged target position error due to the target motion. The Mean X and Mean Z values indicate cross axis errors that are not due to track motion. The Mean Y position error and the SD Y value indicate that the static position accuracy along the y-axis is 16.036 mm ± 9.673 mm.

These X, Y, and Z mean errors and standard deviations are combined to form the Radial Static Position Accuracy values. The Radial Error and RadialSD labels refer to the values that make up the Radial Static Position Accuracy, which is 16.189 mm ± 9.779 mm.

Static Position Error Plot

Figure C-1 is an Excel plot of position error data from Table C-7. This plot provides the Static Position Accuracy Statistics information in a graphical format. Plotted in this figure are curves for: target position versus track encoder position, target position error versus track encoder position, and an Excel linear trendline for the static target position error as a function of track encoder position. Note that there are dual y-axis scales; target position is plotted against the left-hand y-axis and target position error is plotted against the right-hand y-axis. The target position error scaling on the right allows these errors to be magnified and viewed relative to the target position and track encoder positions. The Excel trendline, with an accompanying error equation, provides a method to calculate the approximate position error at any position along the track length. This trendline equation is intended to be used in dynamic accuracy calculations to remove the static position errors from the dynamic position errors. Also included on the figure is a data table with the Mean Static Position Errors, Static Position Standard Deviations, and the Radial Static Position Accuracy values from Table C-7.

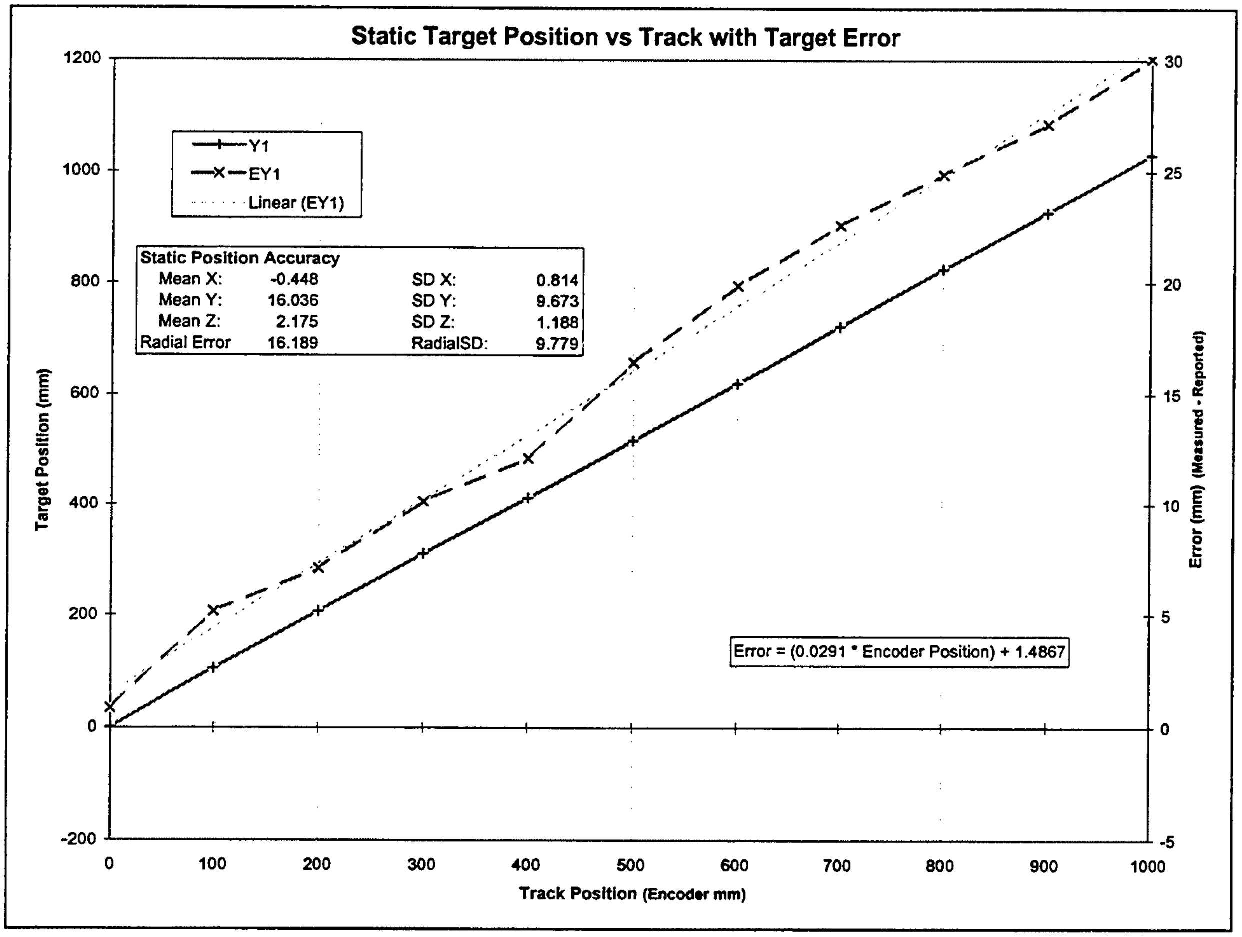

Figure C-1. Static Position Error Plot with Linear Trendline and Equation.

Static Orientation Stability Statistics (Static_Test_Name.rot.std)

Table C-8 is a tracker test program output sample for static orientation stability. This output is stored in a file with a filetype of ".rot.std". The table contains information on the tracking system test parameters, statistical static orientation stability summary, and orientation statistics calculated at each of the static positions of the target.

Table C-8. Static Orientation Stability for Track Position 1

Incremental Test Data	Station 1: ON
Motor Rate = 600.00	Station 2: OFF
Averaged Data	Station 3: OFF
Date and time: Wed Jun 03 11:52:06 1998	Station 4: OFF
Frame Rate = 30 frames/s	Orientation Inertial Mode: ON
Sample Period = 0.0333333333 s	Position Inertial Mode: OFF
Translation Values Calculated	Time Units: microseconds
Translation Enabled	Prediction Interval = 0
InterSense IS-600 Settings	UltraSonicPeriod = 30 ms
Output Format: ASCII	Kalman Filtering: minimal
Units: cm	Post Filtering: jump
Transmit Mode: polled	Tilt Compensation: OFF
Software ID: 2.0.8	Heading Compensation: OFF
System ID: IS300-PRO	Tracking Mode: 6 DOF

Static Orientation Stability

Mean Yaw:	-0.053	SD Yaw:	0.081
Mean Pitch:	-0.019	SD Pitch:	0.038
Mean Roll:	0.001	SD Roll:	0.028
Conic Error:	0.056	ConicSD:	0.09

Encoder	Target	Yaw1	Pitch1	Roll1	EYaw1	EPitch1	ERoll1
0	1	-0.29	0.5565	-0.697	0	0	0
100	1	-0.33	0.5595	-0.751	-0.04	0.003	-0.054
200	1	-0.44	0.531	-0.6935	-0.15	-0.0255	0.0035
300	1	-0.28	0.5765	-0.696	0.01	0.02	0.001
400	1	-0.21	0.547	-0.651	0.08	-0.0095	0.046
500	1	-0.33	0.5605	-0.678	-0.04	0.004	0.019
600	1	-0.27	0.459	-0.673	0.02	-0.0975	0.024
700	1	-0.32	0.57	-0.7225	-0.03	0.0135	-0.0255
800	1	-0.41	0.514	-0.6785	-0.12	-0.0425	0.0185
900	1	-0.45	0.557	-0.7235	-0.16	0.0005	-0.0265
1000	1	-0.44	0.478	-0.695	-0.15	-0.0785	0.002

Table C-8 contains the static orientation stability output for the IS-600 tracker with the track positioned in the tracker motion box at track position 1 (depicted in Appendix B, Figure B-2). The orientation data for this table was recorded at the same time as the position data for producing Table C-7. In this test, the target was attached to the motion track and moved in 100 mm increments along the track length. At each of the target/track positions, 100 target (yaw, pitch, roll) data samples were recorded. These 100 orientation sample data sets are used to perform static orientation stability calculations via the equations of Table 7.

The Static Orientation Means and Static Orientation Errors for each incremental track encoder position are provided in row/column format at the bottom of Table C-8. The Static Orientation Means have column headers of Yaw1, Pitch1, and Roll1. Static Orientation Errors have column headers of EYaw1, EPitch1, and ERoll1. Ideally, since the tracker target is only translated during this test, the Static Orientation Errors should be zero.

Referring to Table 7, the Mean Static Orientation Errors, the Static Orientation Standard Deviation values, and the Conic Static Orientation Stability values are calculated from the static orientation means and errors. These values are listed in Table C-8 under the heading of Static Orientation Stability, where the Mean Yaw, Mean Pitch, and Mean Roll labels refer to the Mean Static Orientation Errors, and the SD Yaw, SD Pitch, SD Roll, and Conic SD labels refer to the Static Orientation Standard Deviations. The Conic Error and ConicSD labels refer to the Conic Static Error and Conic Static Standard Deviation values that constitute the Conic Static Orientation Stability. Summarizing these stability values, the Mean Yaw orientation error is the largest with a value of -0.053 degrees ± 0.081 degrees (1SD), and the Conic Static Orientation Stability is 0.0056 degrees ± 0.09 degrees.

Static Orientation Stability Plot

Figure C-2 is an Excel plot of orientation error data from Table C-8. This plot provides the Static Orientation Stability Statistics information in a graphical format. Plotted in this figure are curves for the target's yaw, pitch, and roll orientation errors versus track encoder position. Also included on the figure is a data table with the Mean Static Orientation Errors, the Static Orientation Standard Deviation values, and the Conic Static Orientation Stability values from Table C-8.

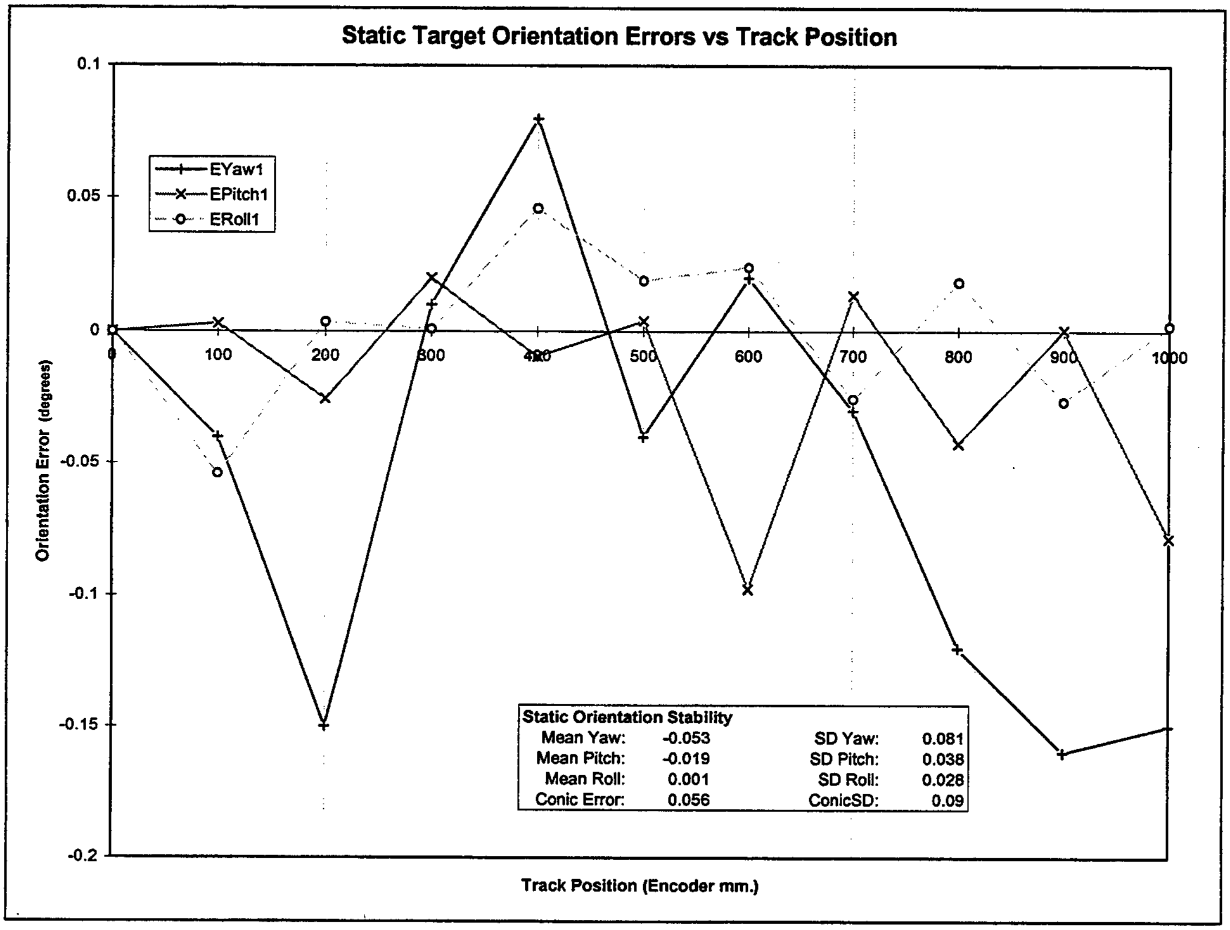

Figure C-2. Orientation Stability Plot for Track Position 1.

SAMPLE DYNAMIC ACCURACY TEST OUTPUT

Dynamic Position Accuracy Statistics (Dynamic_Test_Name.pos.std)

Table C-9 is a tracker test program output sample for the dynamic position accuracy test. The test program stores this output in a file with a filetype of ".pos.std." The table contains information on the tracking system test parameters and a dynamic position accuracy summary. The dual row/column data at the bottom of the table contains the time stamp, track encoder value, and the position errors calculated at each sampling of the tracking target during the phase II dynamic movement.

Table C-9. Dynamic Position Accuracy Statistics, Track Position 1

Dynamic Test Data	
Motor Rate = 600.00	Orientation Inertial Mode: ON
Frame Rate = 30 frames/s	Position Inertial Mode: OFF
Sample Period = 0.0333333333 s	Time Units: microseconds
Translation Values Calculated	Prediction Interval = 0
Translation Enabled	UltraSonicPeriod = 30 ms
InterSense IS-600 Settings	Kalman Filtering: minimal
Output Format: ASCII	Post Filtering: jump
Units: cm	Tilt Compensation: ON
Transmit Mode: polled	Heading Compensation: OFF
Software ID: 2.0.8	Tracking Mode: 6 DOF
System ID: IS300-PRO	
Station 1: ON	Station 3: OFF
Station 2: OFF	Station 4: OFF

Dynamic Position Accuracy Summary

Mean X:	-0.49	SD X:	0.881
Mean Y:	-20.322	SD Y:	11.811
Mean Z:	2.394	SD Z:	1.12
Radial Error:	20.468	RadialSD:	11.897

Date and time: Wed Jun 03 11:56:22 1998

Time	Encoder	Target	EX	EY	EZ	Time	Encoder	Target	EX	EY	EZ
4.402853	3.175	1	-0.30608	-3.40859	-0.30608	5.269653	530.85	1	-0.76056	-17.9756	-0.76056
4.435848	18.125	1	-0.20516	-18.159	-0.20516	5.302564	550.825	1	-0.9769	-19.6493	-0.9769
4.469822	44.625	1	0.30535	-42.3614	0.30535	5.336574	570.65	1	0.10536	-21.479	0.10536
4.502823	70.05	1	0.3698	-53.6865	0.3698	5.369553	590.7	1	-1.30502	-21.9224	-1.30502
4.535843	88.65	1	0.37586	-49.0861	0.37586	5.40252	610.7	1	-0.92229	-23.8239	-0.92229
4.569787	110.325	1	-0.82163	-26.4551	-0.82163	5.436543	630.7	1	-1.13635	-25.0229	-1.13635
4.603766	132	1	0.56155	-29.9363	0.56155	5.469565	650.75	1	-0.26448	-7.47644	-0.26448
4.636787	150.15	1	-0.34609	-27.8818	-0.34609	5.50351	670.8	1	-1.08995	-11.2224	-1.08995
4.669764	170.5	1	0.25081	-27.0344	0.25081	5.53651	690.65	1	0.00466	-10.3774	0.00466
4.702784	191.55	1	0.52075	-32.7854	0.52075	5.569483	710.525	1	-0.51489	-12.6497	-0.51489
4.736789	210.075	1	-0.68782	-31.3045	-0.68782	5.602504	730.525	1	-0.63123	-14.3492	-0.63123
4.769742	230.425	1	-0.10188	-32.8571	-0.10188	5.635531	750.2	1	-1.24299	-14.721	-1.24299
4.802753	251.05	1	0.47811	-35.9845	0.47811	5.668491	770.125	1	-0.35935	-16.35	-0.35935
4.835754	270.175	1	1.26039	-37.1129	1.26039	5.703492	790.975	1	-0.67249	-18.1983	-0.67249
4.869773	290.375	1	0.52906	-20.4091	0.52906	5.736533	810.875	1	-2.18563	-19.0914	-2.18563
4.902738	310.85	1	-1.77354	-19.5733	-1.77354	5.769507	830.6	1	0.2812	-2.32711	0.2812
4.935723	330	1	-1.29035	-20.5253	-1.29035	5.802512	850.7	1	-1.8365	-4.41735	-1.8365
4.968708	350.325	1	-1.80761	-22.7478	-1.80761	5.836489	870.575	1	0.24988	-5.40172	0.24988
5.002708	370.5	1	-1.52167	-24.1239	-1.52167	5.869466	890.525	1	-0.26234	-6.14921	-0.26234
5.035733	390.075	1	-1.04076	-26.0008	-1.04076	5.902442	910.525	1	-0.48326	-8.848	-0.48326
5.068697	410.275	1	0.147	-27.006	0.147	5.936451	930.55	1	0.20176	-10.276	0.20176
5.101611	430.3	1	1.22424	-30.1357	1.22424	5.969491	950.55	1	-3.01272	-11.5612	-3.01272
5.136629	450.925	1	0.11659	-30.5554	0.11659	6.002376	970.525	1	-1.42544	-12.4433	-1.42544
5.170627	470.975	1	-1.11472	-13.6994	-1.11472	6.035371	990.45	1	0.3582	-14.0762	0.3582
5.201582	490.25	1	0.17303	-13.7802	0.17303	6.070354	1006.35	1	-1.27538	6.43149	-1.27538
5.236619	510.8	1	-1.14512	-16.4239	-1.14512						

Table C-9 contains the phase II dynamic accuracy output data for the IS-600 tracker with the track at track position 1 (same as the static accuracy test). For the dynamic test, the test program continuously records the tracking data as the motion track moves the target from the track "home" position to the "end" position. These data samples are used to perform the dynamic position accuracy calculations via the equations of Table 8.

The row/column data at the bottom of Table C-9 contain the time stamp, track encoder value, and track minus target error for every cycle of the tracking system during the phase II movement. At the track speed of 600 mm/sec and sample rate of 30 Hz, there are 51 data samples taken during the track movement of 1000 mm. The track minus target errors, which correspond to the Dynamic Position Errors of Table 8, have column headers of EX, EY, and EZ. The EY values are the position errors related to the track axis, while the EX and EZ are the cross track errors. As the target starts to move along the track from the "home" position, the tracker position output falls behind the track encoder position output and the EY error value indicates this by becoming increasingly negative for a number of samples. After the track velocity stabilizes, the EY value should stabilize about a specific position error value (neglecting any static position errors) that is related to the time lag of the tracking system.

The values listed under the Dynamic Position Accuracy Summary header provide an overview of the dynamic position accuracy by providing the Mean Dynamic Position Errors, the Dynamic Position Standard Deviation values, and the Radial Dynamic Position Accuracy values as defined in Table 8. In the summary section of Table C-9, the Mean Dynamic Position Errors are labeled Mean X, Mean Y, and Mean Z and the Dynamic Position Standard Deviation values are labeled SD X, SD Y, SD Z. The Radial Dynamic Position Accuracy values are labeled Radial Error and RadialSD. The Dynamic Accuracy Summary indicates that the tracker y-axis position accuracy along the 1000 mm length of the track is -20.322 mm ± 11.811 mm. The Radial Dynamic Position Accuracy is listed as 20.468 mm ± 11.897 mm.

Dynamic Position Error Plot

Figure C-3 is an Excel plot of the EY dynamic position errors from Table C-9. Plotted in this figure are the track encoder positions versus time and the EY target errors versus time. The encoder position values are plotted against the y-axis scale on the left, while the EY target errors are plotted against the y-axis scale on the right. In the figure, the EY error value is seen to go negative as the track motion starts. The EY curve then starts following a sawtooth shape with an increasing positive offset over time.

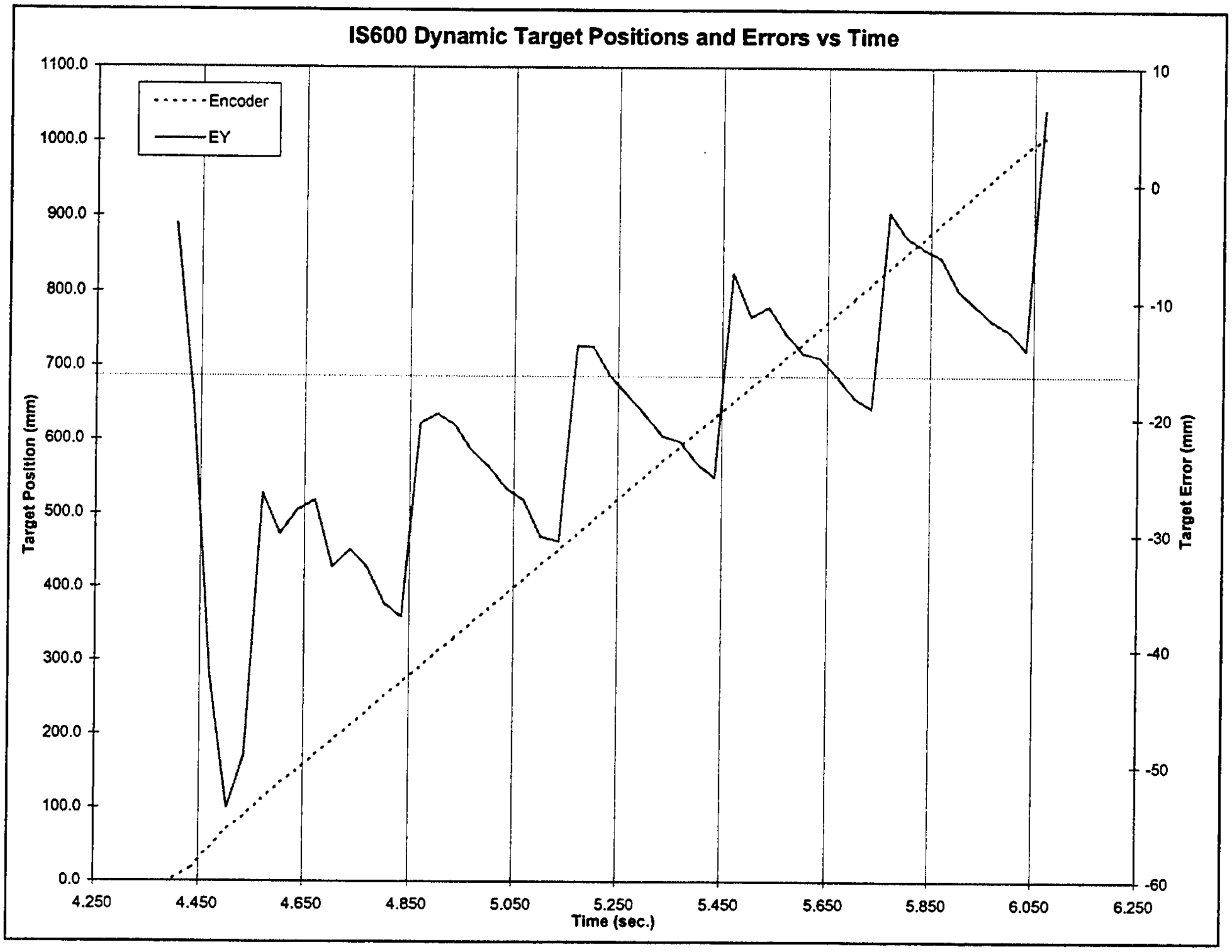

Figure C-3. Dynamic Position Error Plot.

This sawtooth effect illustrates the negative effect of having a different tracking system sample rate as compared to the simulation update rate. The sawtooth shape is due to the fact that the ultrasonic position update period of the tracking system is 30 milliseconds, while the tracker test program frame period is 33.333333 msec (or 30 Hz). The time difference (3.33 msec) causes the tracker test program to delay reading the tracking system output, while the track stage continues to move. When the tracking system output is finally read, the track stage movement during the delay interval increases the position error. This error gradually increases until the tracking system and test program become "in phase" after approximately 10 cycles (33.33 msec / 3.33 msec), and the phasing error is minimized. If the phase error between the tracking system and the tracker test program is reduced, this sawtooth pattern would stretch out over time, but would still occur.

Dynamic Lag Data (Dynamic_Test_Name.txt → Dynamic_Test_Name.xls)

Table C-10 shows the Excel spreadsheet that is used to calculate the dynamic lag time of the IS-600 tracking system based on the phase II target motion data. The table uses the tracking test program output from the dynamic accuracy test. The tracking test program outputs a user named file with a filetype of .txt (e.g., IS600_dynamic.txt) that contains every sample taken during the dynamic test. In Table C-10, the phase II data output by the tracker test program includes the following tab delimited data: sample index, time stamp, track encoder position, and target position (x, y, z). After the output file is imported into an Excel spreadsheet, additional columns of data are added by performing calculations on the original data. These calculations include: time increment between samples (Δt), track encoder position change between samples (ΔEncoder), track velocity (V_{track}), target position change between samples (Δy), Dynamic Position Error (Pos. Error), and the time lag between the track and the target (Lag_{time}).

The Dynamic Position Error and the Lag_{time}, under the column headings of Pos. Error (mm) and Lag(msec), are the values before the static position error is removed. The Static Position Error for each encoder position is calculated using the trendline error equation from the Static Position Error Plot of Figure C-1. These static errors (in mm) are listed under column heading Static Pos. Error. The Corrected Dyn. Error column contains the results of subtracting the Static Pos. Error values from the Pos. Error values. Dividing the Corrected Dyn. Error values by the Track Velocity values produces the time values under the column header Corrected Lag, which are lag values with the effect of the static position errors removed. These corrections applied to the dynamic error and lag values are discussed in the Correcting Dynamic Lag for Static Offsets subsection of the Dynamic Accuracy Tests section of this report.

The Corrected Dyn. Error and Corrected Lag values are averaged to provide an indication of the effects of target motion over the dynamic phase II movement. These averages are labeled Avg. $Error_{corr}$ and Avg. Lag_{corr} .

Table C-10. Phase II Dynamic Accuracy Data and Lag Calculations

Phase II Movement											Lag = Diff / Velocity		Static Pos. Error = (0.0291 * Encoder Position) + 1.4867		
Index	Time	Encoder	X	Y	Z	ΔT	ΔEncoder	Track Velocity	ΔY	Pos. Error (mm)	Lag (sec)	Lag (msec)	Static Pos. Error	Corrected Dyn. Error	Corrected Lag
1	4.402853	3.175	-0.30608	-0.23359	0.09703	0.034	3.175	93.363	-0.201	-3.409	-0.03651	-36.51	1.579	-4.988	-53.42
2	4.435848	18.125	-0.20516	-0.03403	0.19703	0.033	14.950	453.099	14.950	-18.159	-0.04008	-40.08	2.014	-20.173	-44.52
3	4.469822	44.625	0.30535	2.26365	0.09657	0.034	26.500	780.008	26.500	-42.361	-0.05431	-54.31	2.785	-45.147	-57.88
4	4.502823	70.05	0.3698	16.36353	0.29407	0.033	25.425	770.431	25.425	-53.686	-0.06968	-69.68	3.525	-57.212	-74.26
5	4.535843	88.65	0.37586	39.56391	1.18981	0.033	18.600	563.295	18.600	-49.086	-0.08714	-87.14	4.066	-53.153	-94.36
6	4.569787	110.325	-0.82163	83.86994	1.68173	0.034	21.675	638.552	21.675	-26.455	-0.04143	-41.43	4.697	-31.152	-48.79
7	4.603766	132	0.56155	102.0637	1.27845	0.034	21.675	637.894	21.675	-29.936	-0.04693	-46.93	5.328	-35.264	-55.28
8	4.636787	150.15	-0.34609	122.2682	1.87474	0.033	18.150	549.650	18.150	-27.882	-0.05073	-50.73	5.856	-33.738	-61.38
9	4.669764	170.5	0.25081	143.4656	1.47085	0.033	20.350	617.097	20.350	-27.034	-0.04381	-43.81	6.448	-33.483	-54.26
10	4.702784	191.55	0.52075	158.7646	1.56804	0.033	21.050	637.492	21.050	-32.785	-0.05143	-51.43	7.061	-39.846	-62.50
11	4.736789	210.075	-0.68782	178.7705	2.56439	0.034	18.525	544.773	18.525	-31.305	-0.05746	-57.46	7.600	-38.904	-71.41
12	4.769742	230.425	-0.10188	197.5679	2.16094	0.033	20.350	617.546	20.350	-32.857	-0.05321	-53.21	8.192	-41.049	-66.47
13	4.802753	251.05	0.47811	215.0655	2.35782	0.033	20.625	624.792	20.625	-35.985	-0.05759	-57.59	8.792	-44.777	-71.67
14	4.835754	270.175	1.26039	233.0621	2.35454	0.033	19.125	579.528	19.125	-37.113	-0.06404	-64.04	9.349	-46.462	-80.17
15	4.869773	290.375	0.52906	269.9659	2.44779	0.034	20.200	593.786	20.200	-20.409	-0.03437	-34.37	9.937	-30.346	-51.11
16	4.902738	310.85	-1.77354	291.2767	2.84387	0.033	20.475	621.113	20.475	-19.573	-0.03151	-31.51	10.532	-30.106	-48.47
17	4.935723	330	-1.29035	309.4747	2.74064	0.033	19.150	580.567	19.150	-20.525	-0.03535	-35.35	11.090	-31.615	-54.46
18	4.968708	350.325	-1.80761	327.5772	2.83725	0.033	20.325	616.189	20.325	-22.748	-0.03692	-36.92	11.681	-34.429	-55.87
19	5.002708	370.5	-1.52167	346.3761	3.0339	0.034	20.175	593.382	20.175	-24.124	-0.04065	-40.65	12.268	-36.392	-61.33
20	5.035733	390.075	-1.04076	364.0742	3.43063	0.033	19.575	592.733	19.575	-26.001	-0.04387	-43.87	12.838	-38.839	-65.52
21	5.068697	410.275	0.147	383.269	3.52711	0.033	20.200	612.790	20.200	-27.006	-0.04407	-44.07	13.426	-40.432	-65.98
22	5.101611	430.3	1.22424	400.1643	3.92405	0.033	20.025	608.404	20.025	-30.136	-0.04953	-49.53	14.008	-44.144	-72.56
23	5.136629	450.925	0.11659	420.3696	4.02035	0.035	20.625	588.983	20.625	-30.555	-0.05188	-51.88	14.609	-45.164	-76.68
24	5.170627	470.975	-1.11472	457.2756	3.71369	0.034	20.050	589.741	20.050	-13.699	-0.02323	-23.23	15.192	-28.892	-48.99
25	5.201582	490.25	0.17303	476.4699	3.51012	0.031	19.275	622.678	19.275	-13.780	-0.02213	-22.13	15.753	-29.533	-47.43
26	5.236619	510.8	-1.14512	494.3761	3.70693	0.035	20.550	586.523	20.550	-16.424	-0.02800	-28.00	16.351	-32.775	-55.88
27	5.269653	530.85	-0.76056	512.8744	3.10346	0.033	20.050	606.950	20.050	-17.976	-0.02962	-29.62	16.934	-34.910	-57.52
28	5.302564	550.825	-0.9769	531.1757	3.30019	0.033	19.975	606.940	19.975	-19.649	-0.03237	-32.37	17.516	-37.165	-61.23
29	5.336574	570.65	0.10536	549.171	3.69694	0.034	19.825	582.917	19.825	-21.479	-0.03685	-36.85	18.093	-39.572	-67.89
30	5.369553	590.7	-1.30502	568.7777	3.99329	0.033	20.050	607.963	20.050	-21.922	-0.03606	-36.06	18.676	-40.598	-66.78
31	5.40252	610.7	-0.92229	586.8761	3.69006	0.033	20.000	606.667	20.000	-23.824	-0.03927	-39.27	19.258	-43.082	-71.01
32	5.436543	630.7	-1.13635	605.6771	3.38659	0.034	20.000	587.838	20.000	-25.023	-0.04257	-42.57	19.840	-44.863	-76.32
33	5.469565	650.75	-0.26448	643.2736	3.17972	0.033	20.050	607.171	20.050	-7.476	-0.01231	-12.31	20.424	-27.900	-45.95
34	5.50351	670.8	-1.08995	659.5776	3.67681	0.034	20.050	590.661	20.050	-11.222	-0.01900	-19.00	21.007	-32.229	-54.56
35	5.53651	690.65	0.00466	680.2726	2.77295	0.033	19.850	601.515	19.850	-10.377	-0.01725	-17.25	21.585	-31.962	-53.14
36	5.569483	710.525	-0.51489	697.8753	3.16976	0.033	19.875	602.766	19.875	-12.650	-0.02099	-20.99	22.163	-34.813	-57.75
37	5.602504	730.525	-0.63123	716.1758	2.66649	0.033	20.000	605.675	20.000	-14.349	-0.02369	-23.69	22.745	-37.094	-61.24
38	5.635531	750.2	-1.24299	735.479	3.4629	0.033	19.675	595.725	19.675	-14.721	-0.02471	-24.71	23.318	-38.039	-63.85
39	5.668491	770.125	-0.35935	753.775	2.65963	0.033	19.925	604.521	19.925	-16.350	-0.02705	-27.05	23.897	-40.247	-66.58
40	5.703492	790.975	-0.67249	772.7767	2.55613	0.035	20.850	595.697	20.850	-18.198	-0.03055	-30.55	24.504	-42.702	-71.68
41	5.736533	810.875	-2.18563	791.7836	2.05261	0.033	19.900	602.282	19.900	-19.091	-0.03170	-31.70	25.083	-44.175	-73.35
42	5.769507	830.6	0.2812	828.2729	2.64605	0.033	19.725	598.199	19.725	-2.327	-0.00389	-3.89	25.657	-27.984	-46.78
43	5.802512	850.7	-1.8365	846.2827	2.34272	0.033	20.100	608.999	20.100	-4.417	-0.00725	-7.25	26.242	-30.659	-50.34
44	5.836489	870.575	0.24988	865.1733	1.93931	0.034	19.875	584.955	19.875	-5.402	-0.00923	-9.23	26.820	-32.222	-55.08
45	5.869466	890.525	-0.26234	884.3758	2.03573	0.033	19.950	604.967	19.950	-6.149	-0.01016	-10.16	27.401	-33.550	-55.46
46	5.902442	910.525	-0.48326	901.677	1.73265	0.033	20.000	606.502	20.000	-8.848	-0.01459	-14.59	27.983	-36.831	-60.73
47	5.936451	930.55	0.20176	920.2741	1.92927	0.034	20.025	588.815	20.025	-10.276	-0.01745	-17.45	28.566	-38.842	-65.97
48	5.969491	950.55	-3.01272	938.9888	1.42579	0.033	20.000	605.327	20.000	-11.561	-0.01910	-19.10	29.148	-40.709	-67.25
49	6.002376	970.525	-1.42544	958.0817	0.72236	0.033	19.975	607.420	19.975	-12.443	-0.02049	-20.49	29.729	-42.172	-69.43
50	6.035371	990.45	0.3582	976.3738	0.91898	0.033	19.925	603.879	19.925	-14.076	-0.02331	-23.31	30.309	-44.385	-73.50
51	6.070354	1006.35	-1.27538	1012.781	0.11241	0.035	15.900	454.506	15.900	6.431	0.01415	14.15	30.771	-24.340	-53.55
										Avg Error		Avg Lag		Avg Error $_{Corr}$	Avg Lag $_{Corr}$
										-20.32 mm		33.94 msec		-36.65 mm	-61.72 msec

Dynamic Position Error and Lag Plot

Figure C-4 is a Dynamic Position Error and Lag Plot based on the data of Table C-10. On this plot, there are curves for the uncorrected and corrected Dynamic Position Error and Dynamic Lag values. The position error curves are plotted against the left-hand y-axis labeled Position Error (mm), and the lag curves are plotted against the right-hand y-axis labeled Lag (msec). All values are plotted against the x-axis scaling of encoder position in millimeters.

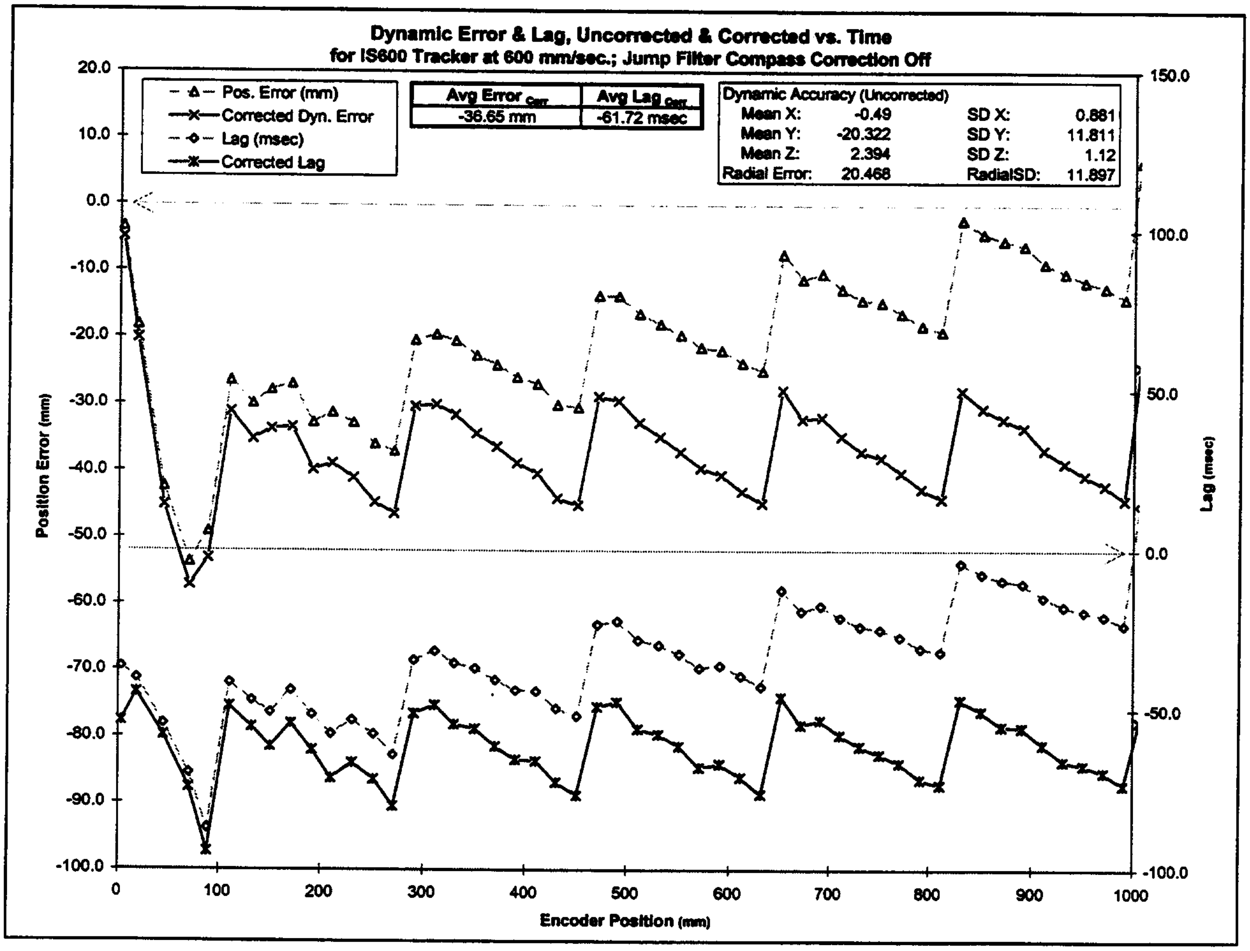

Figure C-4. Dynamic Position Error & Lag Plot for Track Position 1.

The curve labeled Pos. Error (mm) (with data values marked with a triangle) is the same curve as that shown in Figure C-3. The Corrected Dyn. Error curve (with data values marked with an x) shows the corrective effect of subtracting the static position errors. After correction, the position errors are bounded between the approximate levels of -30 mm and -45 mm and are not continually decreasing as before.

The curve labeled as Lag(msec) (with data values marked with a diamond) is plotted using the using the uncorrected Pos. Error data. The curve labeled Corrected Lag (with * data markers) shows the effect of recalculating the dynamic lag after removing the static position errors. The corrected dynamic lag can now be seen to be approximately bounded between a minimum of -50 msec and a maximum of -75 msec.

For summary purposes, there are two data boxes on Figure C-4. The Dynamic Accuracy box contains the uncorrected accuracy summary associated with the uncorrected Dynamic Position Error Curve. The other box contains the corrected Average Dynamic Position Error, Avg. $Error_{Corr}$, and the corrected Average Dynamic Lag, Avg. Lag_{Corr}, which are listed as -36.65 mm and -61.72 msec.

If the phasing error between the tracking system update rate and the tracker test program was eliminated, the dynamic position error and lag values would tend to settle toward their respective minimum values of -30 mm and –50 msec. To eliminate the phasing error, the acceptance of the tracking data would need to be synchronized to the sample rate of the tracking system.

Dynamic Orientation Stability Statistics (Dynamic_Test_Name.rot.std)

Table C-11 is a tracker test program output sample for the dynamic orientation stability test. The test program stores this output in a file with a filetype of ".rot.std." The table contains information on the tracking system test parameters and a dynamic orientation stability summary. The dual row/column data at the bottom of the table contains the time stamps, track encoder values, and the orientation errors calculated at each sampling of the tracking target during the phase II dynamic movement.

Table C-11. Dynamic Orientation Stability Statistics for Track Position 1.

Dynamic Test Data
Motor Rate = 600.00
Frame Rate = 30 frames/s
Sample Period = 0.0333333333 s
Translation Values Calculated
Translation Enabled
InterSense IS-600 Settings
Output Format: ASCII
Units: cm
Transmit Mode: polled
Software ID: 2.0.8
System ID: IS300-PRO
Station 1: ON
Station 2: OFF

Orientation Inertial Mode: ON
Position Inertial Mode: OFF
Time Units: microseconds
Prediction Interval = 0
UltraSonicPeriod = 30 ms
Kalman Filtering: minimal
Post Filtering: jump
Tilt Compensation: ON
Heading Compensation: OFF
Tracking Mode: 6 DOF
Station 3: OFF
Station 4: OFF

Dynamic Orientation Stability

Mean Yaw:	-0.267	SD Yaw:	0.186
Mean Pitch:	-1.196	SD Pitch:	1.226
Mean Roll:	-0.688	SD Roll:	1.226
Conic Error:	1.405	ConicSD:	1.24

Date and time: Wed Jun 03 11:56:22 1998

Time	Encoder	Target	EYaw	EPitch	ERoll	Time	Encoder	Target	EYaw	EPitch	ERoll
4.402853	3.175	1	0.24	0.0525	-0.648	Continued					
4.435848	18.125	1	0.13	0.3025	-0.878	5.269653	530.85	1	-0.24	-1.1275	0.262
4.469822	44.625	1	-0.1	0.2525	-0.818	5.302564	550.825	1	-0.27	-1.5475	0.492
4.502823	70.05	1	-0.2	0.0725	0.002	5.336574	570.65	1	-0.24	-1.6275	0.212
4.535843	88.65	1	-0.05	0.4425	0.272	5.369553	590.7	1	-0.32	-1.3575	-0.088
4.569787	110.325	1	-0.07	-0.0875	-0.818	5.40252	610.7	1	-0.27	-1.3275	-0.368
4.603766	132	1	-0.13	-0.0775	0.232	5.436543	630.7	1	-0.3	-1.3775	-0.128
4.636787	150.15	1	-0.06	-0.1575	2.122	5.469565	650.75	1	-0.31	-1.1875	0.122
4.669764	170.5	1	-0.04	-0.2775	-0.668	5.50351	670.8	1	-0.33	-1.0875	0.012
4.702784	191.55	1	-0.15	0.0125	0.062	5.53651	690.65	1	-0.34	-1.2875	-0.198
4.736789	210.075	1	-0.11	0.0325	-0.028	5.569483	710.525	1	-0.34	-2.2775	-0.878
4.769742	230.425	1	-0.15	0.0125	-0.658	5.602504	730.525	1	-0.36	-2.9275	-1.268
4.802753	251.05	1	-0.15	0.1425	-0.188	5.635531	750.2	1	-0.39	-3.0575	-1.608
4.835754	270.175	1	-0.15	0.1825	0.552	5.668491	770.125	1	-0.37	-3.0975	-1.718
4.869773	290.375	1	-0.14	-0.0475	-0.618	5.703492	790.975	1	-0.49	-3.2675	-2.858
4.902738	310.85	1	-0.19	0.0825	0.412	5.736533	810.875	1	-0.45	-3.5875	-2.818
4.935723	330	1	-0.17	0.3525	0.142	5.769507	830.6	1	-0.44	-3.6075	-3.308
4.968708	350.325	1	-0.19	-0.2275	-0.768	5.802512	850.7	1	-0.47	-3.2175	-2.948
5.002708	370.5	1	-0.16	-0.5175	0.232	5.836489	870.575	1	-0.48	-3.1575	-2.928
5.035733	390.075	1	-0.2	-0.5575	0.662	5.869466	890.525	1	-0.47	-2.9475	-3.348
5.068697	410.275	1	-0.13	-1.0475	-0.178	5.902442	910.525	1	-0.48	-2.5475	-2.958
5.101611	430.3	1	-0.26	-0.5175	-0.068	5.936451	930.55	1	-0.48	-2.1675	-2.188
5.136629	450.925	1	-0.22	-0.9975	0.532	5.969491	950.55	1	-0.52	-2.2675	-2.228
5.170627	470.975	1	-0.23	-0.6975	-0.158	6.002376	970.525	1	-0.54	-2.1275	-1.738
5.201582	490.25	1	-0.25	-0.8175	0.662	6.035371	990.45	1	-0.51	-2.0875	-1.408
5.236619	510.8	1	-0.22	-0.9675	0.342	6.070354	1006.35	1	-0.85	-1.6775	-0.948

Table C-11 contains the phase II dynamic orientation stability output data for the IS-600 tracker with the track located at track position 1. The tracker test program recorded the orientation data as the motion track moved the tracking target from the "home" position to the "end" position. These data values are used to perform the dynamic orientation stability calculations via the equations of Table 10.

The row/column data at the bottom of Table C-11 contain the time stamp, encoder value, and Dynamic Orientation Errors for every sampling of the tracking system. The orientation errors, located under the column headings of EYaw, EPitch, and ERoll, are the differences between the average of the orientation angles from the dynamic phase I samples and the current orientation angles. Since the target is only being translated, the orientation angles should not change and the Dynamic Orientation Errors should be zero.

The values listed under the Dynamic Orientation Stability header provide a summary of the dynamic orientation stability by providing the Mean Dynamic Orientation Errors and the Dynamic Orientation Standard Deviations as defined in Table 10. In this summary section, the Mean Dynamic Orientation Errors are labeled Mean Yaw, Mean Pitch, and Mean Roll and the Dynamic Orientation Standard Deviations are labeled SD Yaw, SD Pitch, and SD Roll. The values that make up the Conic Dynamic Orientation Stability are labeled Conic Error and Conic SD. The summary data indicates that the Conic Dynamic Orientation Stability, is 1.405 degrees ± 1.24 degrees.

Dynamic Orientation Stability Plot

Figure C-5 is an Excel plot of the yaw, pitch and roll Dynamic Orientation Errors from Table C-11. Also provided on the plot is the dynamic orientation stability summary of Table C-11. The orientation angles are plotted in degrees and referenced to the time on the x-axis. As the track movement progressed in time, the yaw error (with + data markers) shows a gradual drift, while the pitch and roll errors show a jumpy random error.

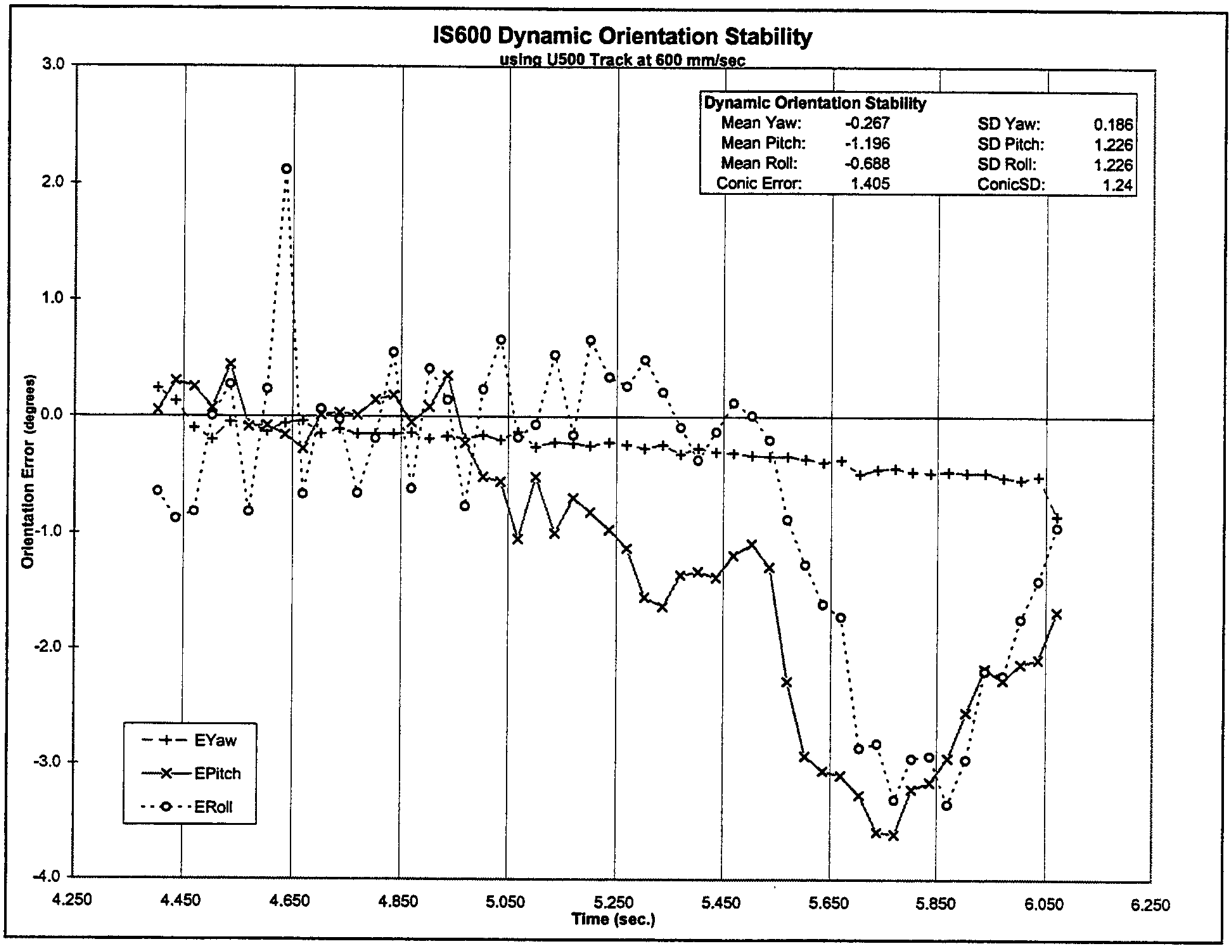

Figure C-5. Dynamic Orientation Stability Plot for Track Position 1.

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