Using Real-Time, 6D Object Tracking to Assemble Large Aerospace Components

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Abstract

This paper will describe a position and orientation (6D) tracking system developed to aid in the assembly of large aerospace components. The tracking capabilities are achieved by simultaneously acquiring coordinate data from three synchronized laser tracker systems. These three trackers are controlled by one master program that coalesces the data into meaningful transform information and presents the operator with simplified guiding prompts. The system is designed to provide machine controller outputs for automated assembly operations as well. This paper will discuss the system requirements, implementation methods, and future applications of this technique.

1 Introduction

Often in assembly applications, it is necessary to track the position and orientation (transformation) of one object relative to another in real-time. This transformation may be used to guide an assembly process or to check that a final assembly meets the required tolerances. In addition, individual points or geometries on the moving object may be evaluated relative to other non-moving objects so that individual sub-component assembly may be controlled. This is particularly useful for aligning bolt holes, pipe interfaces, and other mating components.

This requires more than the standard XYZ position measurement capability often available with real-time measurement systems. To address this need, New River Kinematics developed TransTrack, a 6D transformation tracking application that coordinates simultaneous input from 3 or more XYZ position measurement devices in order to track a transformation. The transformation is then integrated into the graphical measurement software (in this case, SpatialAnalyzer) to provide graphical updates of the moving objects and track tolerances.

This paper is focused specifically on addressing the problem of large object assembly in aerospace applications. This sub-class of the assembly problem poses unique challenges to the 6D tracking problem. These include dealing with huge parts, measurement visibility issues, data synchronization over large areas, tight tolerances, and very expensive parts. The concepts and their implementation, however, apply generally to the 6D transformation tracking problem.

The specific application targeted by this system requires a large scale measurement device (measurements up to 100 feet in distance), laser tracker precision (typically a spatial tolerance of +- 0.010 inches over that volume), and relative rapid update frequency for an automated controller (20 Hz updates).

2 Possible 6D Tracking Systems

There are several possible instrumentation configurations that were considered for this task. These will be presented briefly in this section along with their advantages and disadvantages. For XYZ coordinate measurement, laser trackers will be discussed. This is primarily because the laser tracker is the most well suited to the large object measurement task. Other XYZ measurement devices such as local GPS-like systems, could also be used.

A single laser tracker with ADM (Absolute Distance Measuring) could measure three points on an object then compute a transformation. For many application of this type, this would provide adequate accuracy. However there are several significant drawbacks of this approach. First, the measurement operation might require up to twelve seconds for one measurement cycle. During this measurement cycle the object must remain perfectly stationary. This method requires either relatively limited motion between measurement cycles or some other a priori information about the location and orientation of the component. Lastly, although not very limiting in many cases, some specific geometries are better suited to distributed measurement system for visibility reasons. For example, the longitudinal axis of a long slender cylinder may be determined more precisely by targeting both ends of the cylinder, rather than one single end face of the cylinder.

Three laser trackers with or without ADM could be used to track three points on the moving object. In the case of the ADM measurement option, the object would need to stop motion for the measurement to occur. Because of this limitation, the ADM functionality would only be used to recover from a beam break condition. The ADM measurement would require that the object stop moving before measuring. In the case of a non-ADM tracker, the points would be tracked until a beam is broken. At that time, the object would need to stop, the retro-reflector returned to a home position, then the tracking re-initiated. Alternatively, the object could stop and the beam break condition could be recovered by locating the retro-reflector, locking on to the target, then setting the distance value based on the geometry of the other points. This innovative approach will be presented in greater in following sections.

Another option is to use more than three laser trackers with or without ADM capability. This would add redundant data, thereby increasing the accuracy of the system. In addition, it would allow for more robust beam-break recovery without stopping the motion of the tracked object. As long as at least three targets are tracked, the system could relocate the other "broken" targets in real-time and reset the distance in the interferometer. Initial tests indicate that this process can be accomplished while the tracked object is in motion.

The following section will discuss the approach that was chosen and implemented to solve this problem.

3 Selected Approach

This section will present a brief description of the hardware and software selected for the final system. Additionally, a summary of normal operating procedures will be discussed.

3.1 Hardware Solution

Current ADM technologies require a prolonged period (1-3 seconds) of target stability in order to acquire suitable distance measurements. Because the specified assembly process requires rapid user (or controller) updates while the components are in motion, ADM technologies did not offer any substantial advantages. It was decided that three non-ADM laser trackers manufactured by API (Automated Precision Inc.) would offer an economical solution for the assembly task.

3.2 Software Solution

The accuracy and relatively high frequency requirements of the final application dictated that a software system be selected that provided for simultaneous control and acquisition of data from multiple instruments in a coordinated fashion. The core design architecture of the SpatialAnalyzer package provided all of the above capabilities. To ease operator burdens, a simplified interface was developed that enables an operator to control multiple laser trackers from a single user interface. The operator can control all measurement functions by interacting with just one Windows dialog. This interface, referred to as “TransTrack”, allows one user to control the three trackers in a coordinated fashion to track a six degree-of-freedom transformation. The TransTrack application then controls three other slave applications that are essentially minimal tracker control modules. These individual control modules have been named “MiniTrack”.

Given the large working area and the complexities associated with three laser trackers operating simultaneously, text-to-speech technology is used heavily in the TransTrack application. System health is monitored, and the computer will speak to the operator when error conditions occur. For example, if tracker number three’s beam is broken, the system will say, “Tracker three, beam broken. Stop motion and click recover”. At this point, the operator takes action, then resumes the process.

3.3 System Set-up Description

Figure 1 shows a typical set-up with a core desktop computer running SpatialAnalyzer and TransTrack. TransTrack will maintain network connections to three notebook computers running Mini-Track tracker interfaces. During normal operations these mini-interfaces will require no user input - all control will be handled by the user seated in front of the desktop machine.

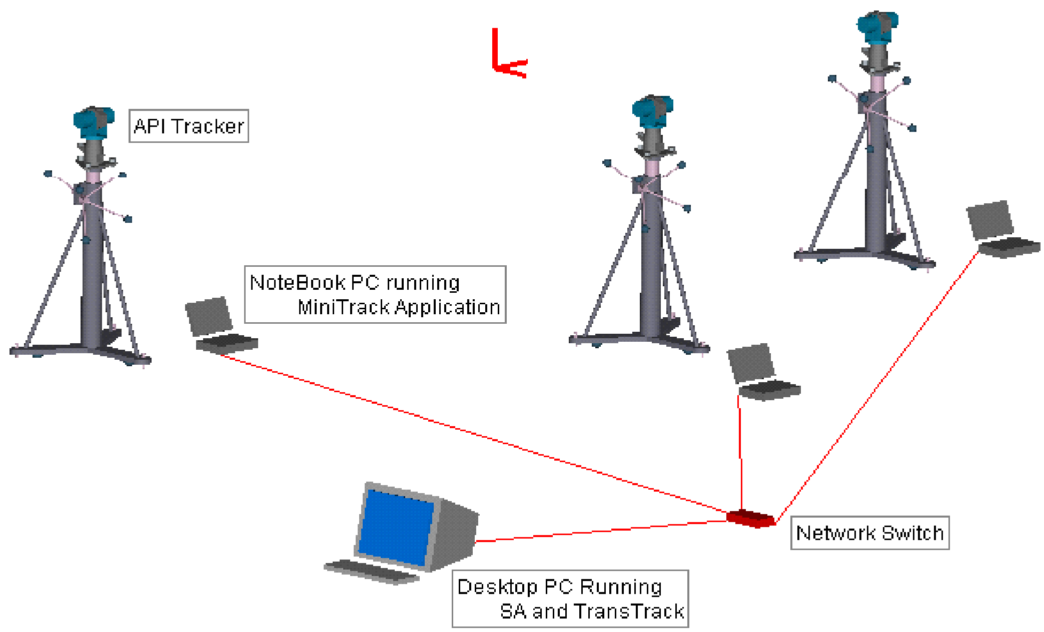

Figure 1 - Typical System Set-up

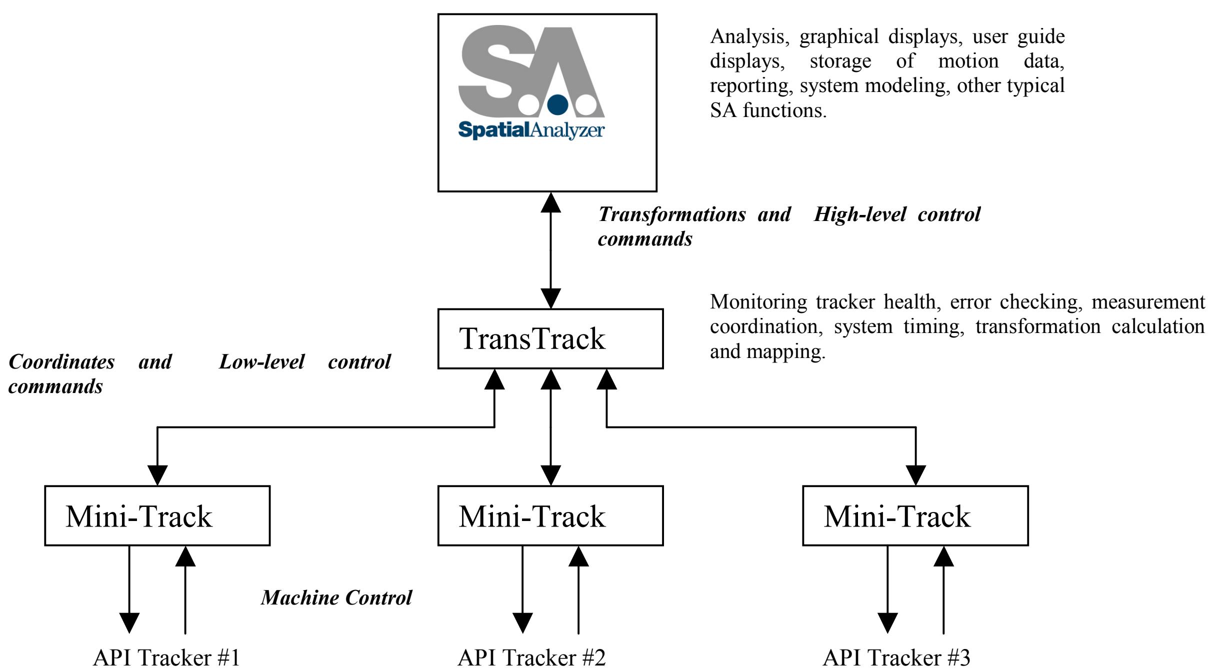

Figure 2 - Communication Connections

The functional communication connections for this system are shown in Figure 2. The main boxes represent pieces of executable software and the arrows represent their inputs and outputs. Brief descriptions of each executable's responsibilities are shown to the right and information passed is shown in italics. All inter-process communication is passed through a TCP/IP compliant 10base-100T network with an integral network switch. Actual tracker control communication is conducted through a standard serial communication link that is an integral part of the API tracker.

3.4 Starting the Trackers and Initializing the System

The system is started by running TransTrack on the desktop computer. The three MiniTrack applications are then started on three separate notebook machines. Three notebooks are used so that that trackers may be located in distant regions of the workspace. Upon starting, each Mini-Track application performs initialization procedures on its respective tracker, and communicates its network parameters to TransTrack. At start-up, each tracker is identified as a primary, secondary, or tertiary instrument. Essentially, the primary instrument will determine the origin of the moving reference system, the secondary will determine an axis direction of the moving system, and the tertiary will determine final orientation by locking a specified plane of the moving system.

3.5 Locating the trackers

The first step after starting the system is to locate all of the trackers relative to a known reference coordinate system. This known reference system may be derived from CAD design data or nominal coordinate information. Any number of nominal points may be used to locate the trackers.

The TransTrack application provides a simple, intuitive check-list interface to aid in this location procedure. There is a simple tabular interface where each column represents an instrument and each row represents a point. The user simply positions a retro-reflector from one instrument in a particular target nest, then clicks in the corresponding cell in a table. The point is measured and that element is marked as completed.

Once a sufficient set of common targets is measured, the user selects the "Locate" option, and all the trackers are located relative to the nominal coordinate data points. If there are any cases of insufficient data, the user is told specifically where additional data is needed. The entire location process should take no more than five minutes once the trackers are warmed up and online.

3.6 Tracking the Object

With the trackers located in the reference frame, the object transform can now be tracked. First, the SMR's are tracked to their respective tracking points as shown in Figure 3. From the three tracking points a coordinate frame is built and updated as TransTrack receives data from the trackers. The point from Tracker 1 becomes the origin of the tracking frame. Tracker 2 provides a point which lies along the X-axis, and the point from Tracker 3 is set to lie in the X-Y plane. As data is received by TransTrack, the tracking frame, or transform, is updated as shown in Figure 4. TransTrack also maintains a set of diagnostics including the distance between the three tracked points, and timing information pertinent to the acquisition time differences.

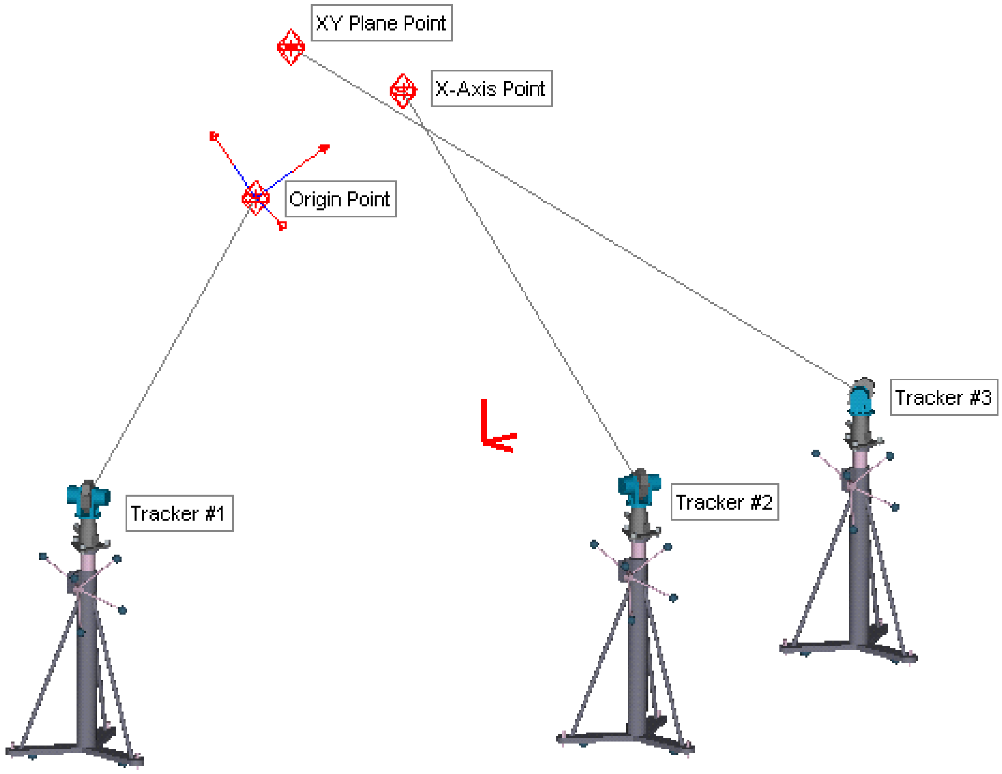

Figure 3. Tracking the Transform

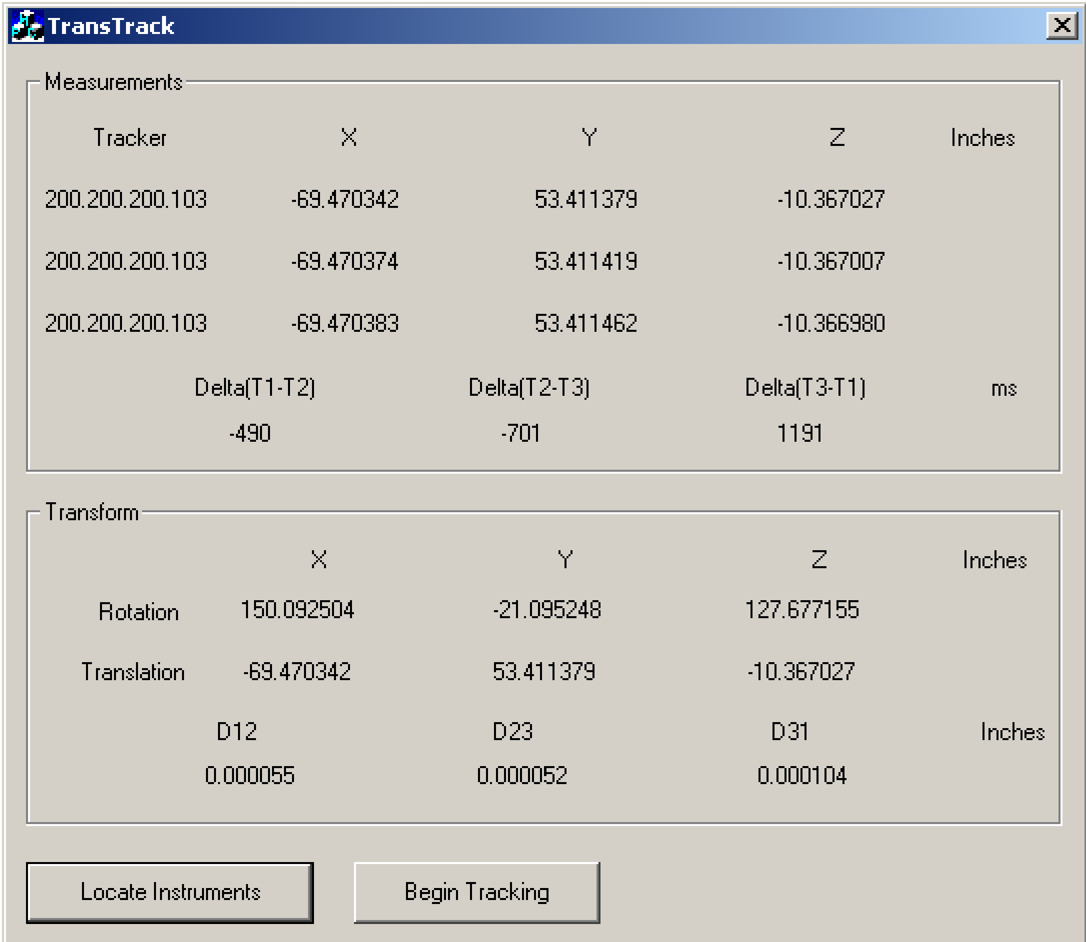

Figure 4. TransTrack Main Dialog with Data Input and Calculated Transform

3.7 System Health

Given the magnitude and expense of aerospace assembly operations, it is imperative that the measurement system provide a continual indication of system health. This was necessary to detect problems including: a bumped instrument, variation in the relative positions of the tracking points, and fluctuation in measurement data rates.

3.7.1 Measurement Synchronization

During object tracking, it is necessary to synchronize the data from the measurement devices so that the time delay between each of the three instruments is minimized. This could be done using hardware triggering methods such as a common trigger wire tied to all the instruments. Once a pulse is detected on the wire all devices could measure at that instant. This triggering capability was not available in the hardware selected for this project. Given the data rates and object motion speed for the tracking task at hand, this was not a major limitation.

Instead of triggering the data, a monitoring approach was used. Each measurement is marked with a time stamp. When a new measurement is received from each device, the time stamps are checked relative to each other so that the delays between the samples are known. These values are constantly monitored and displayed to the user. In addition, a threshold is set so that if the delays exceed an acceptable limit, a red light flashes and the system speaks a brief explanation of the problem to the user.

3.7.2 Geometric Variance Detection

Even if the measurements from the individual trackers were perfectly synchronized, there remains the question of the consistency of measurement values themselves. To monitor this, an inter-point distance method was used.

When transform tracking is initiated, the initial distances between each of the three points are stored. For each transformation update, the current inter-point distances are compared to the initial values. The variation is updated in real-time in the measurement window. If any of the distances vary above a user-defined threshold, a red light flashes and the system speaks the error condition.

This simple check will flag several possible error sources. First, if one of the instruments is bumped then its measured point will vary relative to the others and the inter-point distance check will flag an error. Also, if the moving object flexes, the distances between the points may change, thus triggering an error. Environmental conditions having an adverse effect on the laser tracker (such as a heat source near the beam path) will also cause measurement variation that will be detected by this method.

4 Laser Beam Recovery Modes

Essentially, interferometers measure *relative* distance. Most metrology applications require *absolute* distance measurements. Interferometers can only report absolute distance after an initial distance datum has been accurately set. Typically this process is referred to as *seeding* the interferometer count. Currently, for a single laser tracker there are two methods for seeding the interferometer distance. One may set the distance to a known (or previously measured) value, as in the case of returning home or returning to a remote pocket, or one may use the ADM (Absolute Distance Measuring) technology offered with many of the current generation trackers. ADM measurements present both advantages and disadvantages. The primary advantage of ADM is that it can determine an absolute distance to a target. After an ADM measurement, the interferometer count is seeded with the ADM determined value, and the tracker reports the distance relative to this new datum. The tradeoff of using ADM is that the newly determined datum cannot typically be achieved with the same degree of confidence as an interferometer measurement. Any errors in setting this reference distance will effect all subsequent measurements from this point. For many applications, the accuracy provided by ADM technologies is entirely adequate. Perhaps of greater importance to the proposed measurement system is that ADM technologies require several Under proper conditions ADM measurements For a single tracker system, there simply is no alternative. An operator may use multiple remote pockets, or may rely on ADM accuracy.

4.1 Coordinated Interferometer Distance Setting

Here we propose a new method for setting the interferometric distance used in laser tracker observations. Some background information will be briefly presented followed by a discussion of the new distance setting method.

One of the most important and unique strengths of the selected software is it's ability to simultaneously acquire data from multiple instruments. This technology enables the software to compute and track in real-time the general motion of objects (all six degrees-of-freedom, position and orientation). The following section will describe how we can use multiple tracker simultaneous tracker measurements to effectively recover from a broken beam incident without relying on ADM. This method will prove not only more accurate than ADM, but also significantly faster as well. We will describe the method by using the mathematical abstraction of analyzing the system mobility. Mobility analysis is very helpful in proving concepts, but does not readily aid visualization. On the other hand, geometrical relationships are great for explaining concepts and visualizing, but are very susceptible to misleading special cases, and thus lack the rigor required for a real proof of concept. For these reasons, a combination of methods will be employed in the explanations below.

It should be pointed out, that theodolite systems, actually provide a useful analogy for our discussions. A single theodolite provides only partial coordinate information. This information must be combined with other observations to produce a complete coordinate. Extending the analogy, even two theodolite sightings contain redundant information (all we need is one value from the second sighting), and we utilize the redundant information to indicate the overall quality of a set of observations. This is why pointing error can be computed for theodolite observations. Likewise, we can use the redundant information in multiple tracker sightings to indicate the magnitude of system errors.

4.2 Mobility Analysis

4.2.1 Normal mode of Tracking

As discussed and demonstrated for Boeing previously, we may monitor the position of three separate SMR's attached to a rigid body and from those observations compute the Position and orientation of the object in real time. This process provides us with nine unique pieces of information, the x, y, and z position of each target. We therefore have three redundant degrees-of-freedom in our gathered data (9 sampled – 6 physical = 3 redundant). If we assume the object is rigid, we may use this redundant information to observe the magnitude of system errors (discrepancies). Alternatively, we could assume zero measurement errors, and use these values to monitor object deflections. In either case, we are utilizing the redundant information to at least qualitatively indicate system health.

4.2.2 Broken Laser Path

Now let's assume that we have momentarily obstructed one of the beam paths. If we assume rigidity, two targets alone represent a geometrically degenerate case where the 6 sampled values only represent five independent parameters. Rigidity enforces that the distance between these two targets must remain constant. To represent all possible positions of the object, we may visualize the object spinning about the axis of the two remaining targets. Given this, we know the remaining "lost" target must lie on a circle about this axis. We further know the position and orientation of this circle from the inter-target distances of the three SMR's. Given any one additional piece of information about the third target, we may compute the object orientation. Once we know the object orientation, we can define the position of the lost target and compute the distance to the corresponding tracker. This distance is very accurate since it is computed using only interferometric observations. No ADM process is utilized.

To summarize the process of the software when a single beam is broken.

- Reacquire tracking (this is a very quick process, but represents the biggest delay of this method). Perhaps as much as 0.5 sec in extreme cases.
- Measure azimuth, elevation, and distance for the undisturbed trackers.
- Measure azimuth and elevation from the disturbed tracker.
- Compute the target distance and seed the interferometer of the disturbed tracker.
- Cross check values to indicate overall system performance.

5 Initial Results

The system presented in this paper was delivered on time to the customer and tested on site. The testing showed reliable tracking even under less than ideal (or normal "shop-floor") conditions.

The data rate for the complete transformation update is approximately 30 Hz. This is more than sufficient given the low velocity movements used to position large aerospace components. The bottleneck in the current system is the tracker communication method which is an RS-232 serial link. This currently limits the tracker data rate to around 30 Hz. Since the transformation and health computations require minimal processor time, the 6D tracking rate may be substantially increased by increasing the tracker data rate.

6 Future Developments

Over the next year, it is anticipated that the transtrack application will actually be guiding the motion control system of the automated movers used to position and orient the large assemblies.

The Current work is underway for expanding this application to more than three trackers. The system architecture is implemented for this and the user interface concepts are designed. Final implementation will wait until a specific request is received for such a system.

Also recently developed is a similar system that utilize three or more trackers to track common targets. This multi-lateration interface promises greatly increased accuracies over large volumes for very high-precision applications.

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