Polaris Tool Design Guide

R01
Februrary, 2021
P/N 10005896

Document Revision History

Revision	Date	Description
R01	February, 2021	Initial Release

Published by:

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Read Me First

This guide documents concepts and considerations for the design, construction, and characterization of tools that are used with NDI Polaris Systems.

Before designing a tool, you should understand:

- the information in this guide as it relates to your tool type
- your NDI system, as explained in the guide that accompanied it
- basic wiring concepts and techniques for electronic components, if you are developing active tools

NOTE
NDI does not design tools but provides this document to guide your design. Choices about material, ergonomics, design, application, tool functionality, and material biocompatibility are your responsibility.

Some aspects of tool design are beyond the scope of this document and NDI's areas of expertise. This document cannot anticipate all concerns across the range of tools that can be developed.

For help in understanding the concepts in this guide, or to discuss your tool design, contact NDI. Refer to the contact information below.

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Updates

NDI is committed to continuous improvements in the quality and versatility of its systems. To obtain the best results with your NDI system, and to ensure your design is current, check the NDI Support Site regularly: http://support.ndigital.com

1 Basic Concepts

This chapter introduces tools and markers:

1.1 Introduction

A tool is a rigid structure that has at least three markers attached so there is no relative movement between them. A marker either reflects infrared light emitted by the Position Sensor or emits infrared light itself.

There are three classifications of tools:

- Passive Tools
- Active Wired Tools
- Active Wireless Tools

These classifications are described below.

1.2 Passive Tools

Passive tools are wireless, and incorporate retro-reflective passive markers. To track passive tools, the Position Sensor flashes infrared light from its illuminators. The light floods the surrounding area and reflects off the passive markers back to the Position Sensor.

All Polaris systems can track passive tools.

The three types of passive markers are NDI Passive Spheres, NDI Radix Lenses and reflective discs.

- **NDI Passive Spheres** have a retro-reflective coating. The coating reflects infrared light back to its source, instead of scattering it. NDI Passive Spheres snap-fit to the tool using NDI mounting posts, which are manufactured to firmly hold NDI markers.
- **NDI Radix Lenses** are hemispherical retro-reflective markers that can easily be wiped off if they become dirty. In contrast to the NDI Passive Sphere, the NDI Radix Lens cannot be used directly in the form it is supplied. It must first be incorporated into a tool or mounting base (not provided by NDI).
- **Reflective discs** are flat discs with a retro-reflective coating similar to NDI Passive Spheres. Because they are flat, there is some reduction in off angle performance.

1.3 Active Wired Tools

Active wired tools are electrically connected to the system by a cable and incorporate active markers, either light-emitting diodes or infrared-emitting diodes.To track active wired tools, the Position Sensor detects the light that is emitted by the active markers.

The system controls the markers via a wired connection through the System Control Unit.

Only Hybrid systems can track active wired tools.

1.4 Active Wireless Tools

Active wireless tools are not electrically connected to the system. They incorporate active markers that are powered by battery or by other equipment they are attached to. To track active wireless tools, the Position Sensor pulses its illuminators in a way that is recognized by an infrared receiver on the active wireless tool. The active wireless tool detects the pulse and emits infrared light from the markers in response, which is detected by the Position Sensor.

All systems except the Vega XT can track active wireless tools.

1.5 Tool Type Comparison

Table 1-1 provides a comparison of tool types.

Table 1-1 Comparison of Tool Types

	Passive Tools	Active Tools	Active Wireless Tools
Marker Type	NDI Passive Spheres NDI Radix lenses Reflective discs	Active markers	Active markers
Marker Replacement	NDI Passive Spheres are easily replaced, Radix lenses are permanent. Reflective discs may be permanent or replaced, depending on the design.	Permanently attached.	Permanently attached.
Power Source	Not required	Wired connection to NDI system.	Battery or supporting equipment.
Design Complexity	Marker geometry must comply with unique geometry constraints.	Marker geometry can comply with unique geometry constraints, or standard geometry constraints.	Marker geometry must comply with unique geometry constraints.
System Compatibility	All systems	Hybrid systems only.	All systems except Vega XT.
Electrical Safety		Requires wiring, and may need to comply with the "Electrical Safety Considerations" on page 38.	Requires wiring. May need to comply with electrical safety considerations if the tool is patient-applied.

2 Tool Design Considerations

This chapter will help you narrow down your tool design choices:

2.1 The Right Tool For Me

Before you design a tool, consider the necessary and desired features of the tool. Table 2-1 (markers) and Table 2-2 (tools) provide a comparison of features.

To determine the right tool for your application, consider the following:

2.1.1 Tool Type Considerations

- Does the tool need to be wireless?
- Is the tool a probe tool?
- Will the tool be used as a reference tool?
- Is the tool a calibrator or pivot block, used to determine the tool tip offset?

2.1.2 Design Considerations

- Does the intended use of the tool require transformations with five or six degrees of freedom?
- How much will the tool be rotated during use?
- What is the required accuracy of the tool?
- What size does the tool need to be?
- Will this tool be used simultaneously with other tools?

2.1.3 Construction Considerations

- How will the tool be used (held by hand, attached to an object, etc.)?
- Will the tool require sterilization, or should it be disposable?

2.1.4 Marker Comparison

Table 2-1 provides a comparison of marker features.

Table 2-1 Marker Comparison

Marker Type	Disposable	Wipeable	Cost	Form Factor	Integration Effort	Maximum Marker Angle
NDI Sphere	✓		$	medium	medium	±90°
NDI Radix Lens		✓	$$	largest	high	±60°
Active / Active Wireless		✓	$$$	smallest	high	±60°
Disc	Depends on material		$-$$$	smallest-largest	low	±45°

2.1.5 Tool Comparison

Table 2-2 provides a comparison of tool features.

Table 2-2 Tool Comparison

Feature	Wireless	Unique Geometry Required	Power Source Required	Resistance to Reflection Interference
Passive, single face, sphere	✓	✓		✓
Passive, multi face, sphere	✓	✓		✓
Passive single face, radix	✓	✓		✓
Passive, multi face, radix	✓	✓		✓
Passive, single face, disc	✓	✓		✓
Passive, multi face, disc	✓	✓		✓
Active wireless, single face	✓	✓	✓	✓
Active wireless, multi face	✓	✓	✓	✓
Active wired, single face				✓
Active wired, multi face				✓

2.1.6 Marker Geometry

Marker geometry refers to the formation of markers on the face of a tool.

- Active tools can use standard geometry (where symmetrical patterns are acceptable) or unique geometry (where the segment length and segment angles between markers must differ).
- Passive tools must use unique geometry.

Refer to “Marker Geometry” on page 13 for more information and the benefits of the different approaches.

2.2 Tool Design Best Practices

Consider the following best practices to design a tool that is as accurate as possible.

- A tool should have at least four markers.
- Markers should be spread apart as much as possible. Refer to Table 4-1 on page 14 for the minimum recommended distances.
- Reference tools should be as large as possible.
- The area of interest should be inside the reference tool, if possible.
- Markers along a probe axis should be furthest apart.
- The tip on a probe should be as close as possible to the markers.
- Passive tools should not be made of infrared-reflective surfaces.
- The user should determine the tip offset of a probe before every use.

2.3 Tool Material

When choosing a material for the tool, consider the following material-related issues:

- Ergonomic factors such as weight, size, shape, ease of manipulation, tactility character.
- Rigidity of the material. Marker positions must remain fixed with respect to one another.
- The environment where the tool will be used. For instance, tools manufactured using ferrous material could cause interference if used in conjunction with MRI equipment.
- Sterilization and cleaning requirements of the tool. If the tool will require sterilization, consider what methods will be used. Certain sterilization methods can damage anodized metal.
- Reflectivity of the tool surface. A reflective tool can reflect infrared light from the illuminators back to the Position Sensor, which may interfere with tracking. This is usually not a concern for active tools.
- The opacity of the material. NDI recommends opaque material when possible for the following reasons:
    - A translucent or transparent material on a multi-faced tool might allow the system to detect markers on faces it is not currently tracking. The markers may also be partially occluded by other markers, causing their sensor images to merge and increase measurement error, as described in “Marker Occlusion Issues” on page 58.
    - Translucent or transparent material may also introduce error into the measured position of a marker, affecting system performance.

2.4 Minimize Reflections

To minimize the reflections from the tool surface, consider the shape and finish of the tool. This is less of a concern with active tools, which are often brighter than passive tools.

Shape: A curved tool will cause fewer reflections than a flat tool. A flat tool can act like a mirror and reflect back most of the light. A curved tool with a small radius will reflect light in different directions, so less light is reflected back to the Position Sensor.

Finish: Bead-blasting a tool before applying a finish reduces reflectivity. Bead-blasting roughens the surface so less light is reflected toward the Position Sensor.

The apparent reflectivity of a surface under visible light does not always indicate the reflectivity of the surface under infrared light. For example, matte black paint appears to absorb a lot of light, but it may still reflect infrared light. The NDI Toolbox Capture utility can be used to test the infrared reflectivity of the tool material.

3 System Overview

This chapter provides an overview of the Polaris platform, which may be helpful if you are new to the system you are working with:

3.1 System Overview

Before you design a tool for your system, you should review the user guide for your system. However, this chapter provides a high level overview of the Polaris platform.

The Polaris Vega, Vicra, and Spectra Systems are optical measurement solutions that use near-infrared light to calculate the 3D positions of markers attached to tools. The Position Sensor in the system can track multiple tools at once within a pre-calibrated measurement volume. Measurement data is captured for integration into tool navigation and visualization applications.

A typical Polaris System includes one or more Position Sensors, one or more wireless tools that are tracked by the Position Sensor(s), and a host computer. A Hybrid Spectra system would also include a System Control Unit for integrating active wired tools.

3.2 System Operation

All Polaris systems operate in the following manner:

1. The Position Sensor emits infrared light from its illuminators, similar to the flash on a conventional camera.
2. The infrared light floods the surrounding area and reflects back to the Position Sensor off passive markers (on passive tools), or triggers markers to activate and emit infrared light (on active wireless tools). Active wired tools are usually activated by a signal from the system.
3. Using the reflected or emitted light, the Position Sensor measures the positions of the markers, and calculates the transformations (the positions and orientations) of the tools to which the markers are attached.
4. The Position Sensor sends the transformation data, along with status information, to the host computer for collection, display, and further manipulation.

3.3 System Images

Below is an image of each Polaris position sensor. Depending on your system, you may also have a USB converter to support serial communications, a power adapter and cable, and a system control unit (for connecting wired tools to hybrid systems).

3.3.1 Vega Position Sensor

There are several different variants of the Vega Position Sensor, each offering a different combination of features, which are documented in detail in the user guide supplied with each system. Note that custom enclosures and/or branding are available, so your Position Sensor may not look exactly as depicted here.

3.3.2 Spectra Position Sensor

Note that custom enclosures and/or branding are available for Spectra Position Sensors, so your Position Sensor may not look exactly as depicted here.

3.3.3 Vicra Position Sensor

4 Design Concepts

This chapter describes the concepts you must be familiar with when designing a tool:

4.1 Tool Definition File

Each tool needs a tool definition file to describe the tool to the system. The file is created with NDI 6D Architect software, during the tool characterization process. It is formatted as a .rom file and is stored on the tool's serial read only memory or manually uploaded to the system software.

Tool definition files contain a variety of information, such as:

- Number of markers and the placement of the markers relative to one another
- Number of faces
- Marker type
- Whether the tool is 5DOF or 6DOF
- Manufacturer information, such as the tool manufacturer's name and the tool's part number
- Definition of GPIO lines
- Minimum number of markers to track
- Marker normals and face normals
- Maximum 3D error

4.2 Marker Geometry

Marker geometry refers to the formation of markers on the face of a tool and the associated algorithms that identify individual markers based on the formation. Vega and Spectra systems can track a tool using one of two methods: standard geometry or unique geometry. Vicra systems use unique geometry only.

The default is standard geometry so a tool must be labeled as a unique geometry tool in the tool definition file for the system to track it using the unique geometry algorithm.

Standard geometry is supported for active wired tools only.

In a **standard geometry tool**, it is acceptable for markers to be placed in a symmetrical pattern, with common segment lengths and segment angles. This is acceptable because active markers illuminate in a known sequence that the system uses to identify individual markers.

In a **unique geometry tool**, the segment lengths and segment angles must all be unique because this information is used to identify individual markers instead of the sequence of illumination. Unique geometry tools that are used together must have sufficiently different marker geometry, so the Position Sensor can distinguish between them.

For a more detailed comparison, refer to "Standard Versus Unique Geometry" on page 16.

4.2.1 Minimum Distance Between Markers

A minimum distance between markers must be maintained in your tool design, as specified in Table 4-1.

Table 4-1 Minimum Distance Between Markers

Position Sensor & Volume	Minimum Distance
Vega/Spectra Pyramid Volume	40 mm
Vega/Spectra Extended Pyramid Volume	50 mm
Vicra	30 mm

The minimum distance between markers allows the Position Sensor to distinguish the markers throughout the characterized measurement volume, at an angle of 45° at the back corner of the measurement volume. If the markers are closer together, the system may not track the tool reliably throughout the measurement volume, because the marker images may merge as described in "Marker Occlusion Issues" on page 58.

4.2.2 Passive and Active Wireless Tool Design Constraints

Passive and active wireless tools must comply with the following constraints:

Table 4-2 Passive & Active Wireless Tool Design Constraints

Requirement	Specification
Tool definition file	See "Characterizing a Tool" on page 62 to create a tool definition file.
Marker limit on single-faced tools	3-6 markers, NDI recommends using at least 4 markers per tool.
Marker limit on multi-faced tools	Up to 20 markers, 3-6 markers per face. NDI recommends using at least 4 markers per face.
Minimum distance between markers	Refer to Table 4-1 on page 14 for the recommended minimum distances.

Given the wide range of tools that might be constructed, it is not possible to provide specific advice on the number of markers to use, or their placement.

Please contact NDI technical support to discuss more specific implementations. Refer to "Contact Information" on page vi.

4.2.3 Active Wired Tool Design Constraints

Active wired tools must comply with the following constraints:

Table 4-3 Active Wired Tool Design Constraints

Requirement	Specification
Tool definition file	See "Characterizing a Tool" on page 62 to create a tool definition file.
Marker limit on single-faced tools	3-20 markers.
Marker limit on multi-faced tools	Up to 20 markers, at least 3 markers per face. NDI recommends using at least 4 markers per tool or face.
Minimum distance between markers	Refer to Table 4-1 on page 14 for the recommended minimum distances.
Marker distribution	Markers should be distributed as evenly as possible between columns in the tool wiring matrix. For more information, see Figure 8-2 on page 41.
Unique geometry	An active wired tool may be tracked using standard or unique geometry. Refer to "Unique Geometry Constraints" on page 15 and Table 4-5 on page 16 for more information.

4.2.4 Unique Geometry Constraints

The Position Sensor recognizes active wireless tools and passive tools solely by marker geometry. When using unique geometry the following constraints apply.

Table 4-4 Unique Geometry Constraints

Constraint	Specification
Minimum Required Segment Length Difference	3.5 mm
Maximum Markers Per Face	6

Tools of the same classification that are tracked simultaneously must be compatible with one another, as described in "Tool Compatibility" on page 17. This ensures the tools have sufficiently different geometry so the Position Sensor can distinguish between them.

Tools of different types are tracked in different frames and do not need to be compatible with one another.

4.2.5 Standard Versus Unique Geometry

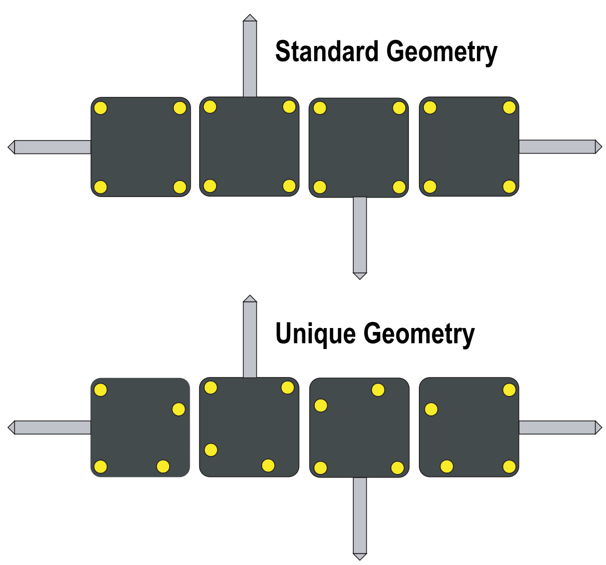
Table 4-5 contrasts the characteristics of standard and unique geometry tools.

Table 4-5 Standard versus Unique Geometry

	Standard Geometry	Unique Geometry
Design complexity	Less complex than unique geometry. Fewer design constraints. Multiple tools with the same geometry can be used together.	More complex than standard geometry. Must comply with the unique geometry constraints. If multiple unique geometry tools are used together, they must be compatible with one another.
Acquisition time while tracking	Slower acquisition time than unique geometry. Standard geometry tools require an additional lock-on stage before the tool can be tracked. During this lock-on stage, the system controls each marker on the tool separately to properly identify them. The tool must move in a slow, constant motion.	Faster acquisition time than standard geometry. No additional lock-on stage needed. This is particularly useful after a tool goes missing, and provides more stability when tracking rapid motions.
Tool compatibility	Active wired tools only.	Active, passive, or active wireless tools.

Figure 4-1 shows four orientations of a standard geometry tool and four orientations of a unique geometry tool. The Position Sensor must have previously identified each of the markers in order to identify the orientation of the standard geometry tool, but can determine the orientation of the unique geometry tool solely by marker geometry.

Figure 4-1 Standard and Unique Geometry Tools



4.3 Tool Compatibility

Tools that are tracked simultaneously must meet a number of compatibility constraints. The following terminology is necessary for understanding tool compatibility constraints:

Segment Length: The distance between two markers on a tool.

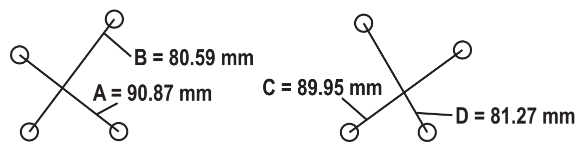
Segment Pair: Two segments on the same tool.

Segment Angle: The angle between two segments.

Like Segments: Segment lengths that are within 3.5 mm of each other.

Like Segment Pairs: Two segment pairs, each on a different tool or face, such that each segment in one pair has a like segment in the other pair. This is illustrated in Figure 4-2, where segments A and B form one segment pair, and segments C and D form another segment pair. A and C are like segments, and B and D are like segments, so segment pair AB and segment pair CD are like segment pairs.

Figure 4-2 Like Segment Pairs



4.3.1 Tool Compatibility Constraints

Tools that are tracked simultaneously must meet the following compatibility constraints:

If two tools are of the same classification (either passive, active wireless, or active wired), they must meet the following tool compatibility constraints:

- Like Segment Pair angles must differ. See table Table 4-6.

Table 4-6 Like Segment Pairs Angle Constraint

Constraint	Specification
Like Segment Pairs Angle Constraint	Segment angles must differ by at least 2.0º. This applies to faces on a multi-faced tool as well, both within the tool and between tools.

- A passive tool can have the same marker geometry as an active wireless tool, since passive and active wireless tools are not tracked in the same frame.
- Tools that are mirror images of each other cannot be used together, since they have the same segment lengths and angles.

4.3.2 Marker Count and Unique Geometry

The more markers there are on a tool the greater the complexity of the unique geometry tool design. The following aspects of tool design become more complicated as marker count increases:

- The number of segments on the tool increases. This complicates tool design, because the segments must all differ in length by at least 3.5 mm.
- It also increases the potential number of segment pairs if multiple tools are used simultaneously. The total number of segments in a tool is $\frac{M \times (M-1)}{2}$, where M is the number of markers.
- The size of the tool increases. The minimum length of the longest segment is *x* mm + [(S - 1) × *y* mm], where S is the number of segments, *x* is the minimum distance between markers, and *y* is the minimum difference between segment lengths.
- The number of segment angles increases. The total number of segment angles is $\frac{S \times (S-1)}{2}$, where S is the number of segments.

These effects are illustrated in Table 4-7.

Table 4-7 Effects of Using More Markers

Number of Markers	Number of Segments	Minimum Length of Longest Segment	Number of Segment Angles
3	3	(*x* + 2*y*) mm	3
4	6	(*x* + 5*y*) mm	15
5	10	(*x* + 9*y*) mm	45
6	15	(*x* + 14*y*) mm	105

Tools of the same classification that are tracked simultaneously must be compatible with one another, as described in “Tool Compatibility” on page 17. This ensures the tools have sufficiently different geometry so the Position Sensor can distinguish between them.

4.4 Multi-Faced tools

A multi-faced tool is a tool whose markers are arranged onto surfaces that face different directions or span a large area. The Position Sensor tracks only one face on a tool at a time

A multi-faced tool might be necessary if the intended application requires the tool to be rotated beyond the maximum marker angle (see “Maximum Marker Angle” on page 49).

4.4.1 Face Normal

Each face is assigned a face normal in the tool definition file. The face normal is a vector that points in the same direction as the tool face, which allows the system to determine which direction each tool face is facing.

The system will track the face that most directly faces the Position Sensor (that is, the face with the smallest angle between the face normal and the sensors in the Position Sensor). If fewer than the minimum number of markers (see “Minimum Number of Markers” on page 51) are visible on the face most directly facing the Position Sensor, the system will attempt to track another face.

4.4.2 Marker Normal

A marker normal is a vector of unit length, and points in the same direction as the marker. Every marker on a tool has a marker normal. Setting marker normals allows the system to make use of the maximum marker angle parameter (described in “Maximum Marker Angle” on page 49). The maximum marker angle causes the system to stop using the marker data once the off-axis viewing angle has reached a certain level, reducing the possibility that the system will calculate inaccurate transformations.

4.4.3 Hysteresis

The system has a hysteresis of 2° when determining whether to switch faces. The system will determine the angle between the Position Sensor and each face of the tool. If the face with the smallest angle is 2° smaller than the current face’s angle, the system will switch to the new face. This prevents the system from switching back and forth between two faces when both faces are at the same approximate angle to the Position Sensor.

4.4.4 Multi-Faced Tool Constraints

Multi-faced tools must comply with the following constraints:

Table 4-8 Multi-Faced Tool Constraints

Position Sensor & Volume	Minimum Distance
Number of markers per face	3 to 6 markers per face, to a maximum total of 20 markers
Can markers be shared between faces	Yes
Maximum number of faces	8
Are unique geometry constraints required	Yes. Refer to “Unique Geometry Constraints” on page 15.
Tool face compatibility	Tool faces must be compatible, meeting the same compatibility constraints outlined for tools in “Tool Compatibility” on page 17.

4.5 Coordinate Systems

There are two coordinate systems to be aware of when designing tools:

- Global Coordinate System
- Local Coordinate System

4.5.1 Global Coordinate System

The Position Sensor’s global coordinate system is described in detail in the user guide that accompanied your system. The global coordinate system has an origin located at the Position Sensor and three axes (X, Y, Z). The system will report the transformations of tools in the global coordinate system unless you use a reference tool, in which case software can calculate and report transformations in the local coordinate system of the reference tool.

The global coordinate system is defined during manufacturing and cannot be changed. The Position Sensor's global coordinate system is described in the user guide for the system.

4.5.2 Local Coordinate System

A local coordinate system is a coordinate system (three axes: X, Y, Z, and an origin) assigned to a specific tool. It is usually defined in NDI-provided software, such as NDI 6D Architect. When the system tracks a tool, it reports the transformations of the origin of the tool. The marker and face normals are set in the tool's local coordinate system.

Tips for defining the local coordinate system:

- Be consistent in defining local coordinate systems for a suite of tools; this makes application development easier. For example, it is conventional on a probe to align the z-axis to the probe shaft, with the positive z-axis pointing away from the tool tip.
- It is possible to define the origin of a probe tool at the tip of the probe; however, if the tool is later bent, the origin will no longer be located at the tip. NDI recommends pivoting the tool or using a calibrator to determine the tool tip offset before each use.

4.6 Degrees of Freedom

Position Sensors can track tools in either 6 Degrees of Freedom (6DOF) or 5 Degrees of Freedom (5DOF). These are defined as follows:

- **6DOF:** The three translation values on the X, Y, and Z axes and the three rotation values roll, pitch and yaw
- **5DOF:** The three translation values on the X, Y, and Z axes and yaw and pitch. Disregard roll, as it cannot be tracked in a 5DOF tool

NDI recommends using 6DOF tools, though 5DOF tools can be used and are sometimes easier to design from an ergonomic perspective. With a 5DOF tool, however, roll around the cylindrical axis is always undefined. The software will report all six coordinates but the roll values will not contain meaningful data.

The system will report 5DOF for a tool when the markers on the tool are collinear. The system will not be able to measure the rotation of the tool about the axis on which the markers are positioned. Therefore, the system will report the 3D position but only the 2D orientation of the tool.

The system will report 6DOF for a tool when the markers on the tool are not collinear. The system will report the 3D position and 3D orientation of the tool. If you are designing a 6DOF tool, you must consider both the marker geometry and the tool tracking parameter values, to ensure that there are no circumstances under which the system may track only a collinear subset of the markers on the tool.

See "Tool Tracking Parameters" on page 48 for information on how to set values for the tool tracking parameters in the tool definition file.

4.7 Sampling Rate

The sampling rate is the rate at which the system reports transformations for all the tools being tracked. The number and classification of tools being tracked affects the sampling rate. Table 4-9 shows the sampling rate for the supported system and tool combinations.

Table 4-9 Sampling Rate by System and Tool Type

	Vega ST/VT	Vega XT	Spectra	Vicra
Passive	60 Hz	250 Hz	60 Hz	20 Hz
Active	60 Hz	Not supported	60 Hz	Not supported
Active Wireless	60 Hz	Not supported	60 Hz	20 Hz

If you track different tool types at the same time, the sampling rate for each tool goes down. Table 4-10 illustrates how this works for Vega and Spectra Systems.

Table 4-10 Sampling Rate with Different Tool Types - Vega and Spectra

	Frame 1	Frame 2	Frame 3	Frame 4	Frame 5	Frame 6
Passive	Passive	Passive	Passive	Passive	Passive	Passive
Passive and Active Wireless	Passive	Active Wireless	Passive	Active Wireless	Passive	Active Wireless
Passive, Active Wireless, and Active	Passive	Active Wireless	Active	Passive	Active Wireless	Active

The sampling rate for Vicra behaves in a different way. Internally, the sampling rate is 60 Hz but it is limited to 20 Hz, with data-less frames incorporated into the sequence, as shown in Table 4-11.

Table 4-11 Sampling Rate with Different Tool Types - Vicra

	Frame 1	Frame 2	Frame 3	Frame 4	Frame 5	Frame 6
Passive	Passive	No Data	No Data	Passive	No Data	No Data
Passive and Active Wireless	Passive	Active Wireless	No Data	Passive	Active Wireless	No Data

For more information about the sampling rate for your system, refer to the user guide that came with it.

4.8 Points of Interest

Points of interest are points on or near a tool where accuracy is most important and is determined by the tool's intended use. When designing a tool, it is important to understand and consider the relationship between points of interest, the origin of the tool's local coordinate system, and the resulting transformations that will be returned by the system. The aim is to design a tool that produces the greatest accuracy at the point(s) of interest.

Points of interest are an important consideration when placing markers on the tool. The closer the markers are placed to the point(s) of interest, the greater the accuracy at the point(s) of interest. Ideally the origin of the local coordinate system, markers, and point(s) of interest would all be the same. In practice this is not always possible, and in some cases not even advisable.

Consider a simple probe. It is not possible to place the markers at the probe's tip because of physical restrictions. However, placing the markers as close to the tip as possible will minimize the offset vector required and improve accuracy.

The point of interest must be rigidly fixed relative to the markers.

4.9 Axes of Interest

Similar to a point of interest, an axis of interest represents an imaginary vector in (or projected from) a tool where measurement accuracy is most important. For example, if the tool is a probe that needs its trajectory to be in a particular direction before being used, the axis of interest is an imaginary line traveling along that trajectory.

The same criteria discussed for points of interest also apply to axes of interest. Axes of interest need to be considered when placing markers and defining the tool's local coordinate system. The closer one of the markers is aligned with an axis of interest, the greater the accuracy of that axis of interest.

4.10 Offset Vectors

Although you may be able to place markers so their origins fall on either the point of interest or axis of interest, there are situations in which this may be physically impossible. For example, you may not be able to embed a marker inside a probe tip because the tip is too small, or because it is likely to bend or break.

In these situations, you apply an offset vector to describe the location of the point of interest with respect to the tool's origin. This value can be written into a tool definition file, permanently stored in the user portion of the SROM device and applied using your application software. It can also be calculated as part of the tool's application, producing an independent and constant value that is applied to collected data in real-time.

> **NOTE**
> To determine an offset vector for a tool with a tip (otherwise known as the tip offset), perform a pivot. Instructions are provided in "Tool Tip Offset" on page 43.

4.11 Groups

Groups are sets of markers on active wired tools that are activated at different times. Groups are required when it is necessary to place two markers close together. Refer to Table 4-1 on page 14 for the recommended minimum distance between markers in a group. Using groups essentially halves the sampling rate for each tool.

The following constraints must be observed when using groups on a tool:

- Groups can only be used on active, standard geometry tools.
- A maximum of two groups per tool can be defined.
- If markers are on the same face but are close to each other, they must be in separate groups.
- If markers are close to each other but are not defined to be on the same face, they can be in the same group.

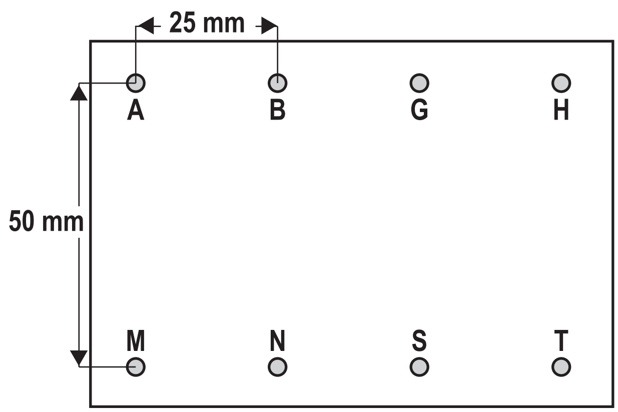
- Each marker can only be in one group (but can be assigned to more than one face).
- Within each group, markers should be distributed as evenly as possible between columns in the tool wiring matrix. For more information on the tool wiring matrix, see Figure 8-2 on page 41.Groups on a Single-Faced Tool

Figure 4-3 illustrates an 8-marker, single-faced tool. The marker letters correspond to the markers' positions in the tool wiring matrix on Figure 8-2 on page 41.

The markers can be divided into faces and groups as follows:

- **Faces:** Since all eight markers are visible to the Position Sensor at the same time, this tool should be defined as a single face.
- **Groups:** The distance between columns of markers is less than 50 mm, so the markers must be divided into two groups. (Note: For the Vega and Spectra pyramid volumes, markers only need to be 40 mm apart.) One possible way to divide the tool into two groups is to put markers A, G, M, and S in group 1, and markers B, H, N and T in group 2. Notice that the markers in each group are evenly divided between the columns of the tool wiring matrix.

Figure 4-3 Groups on a Single-Faced Tool



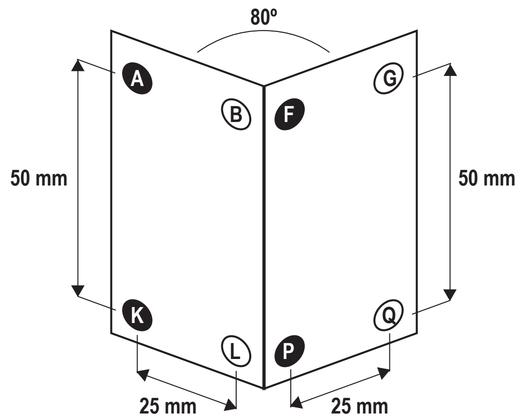
4.11.1 Groups on a Multi-Faced Tool

Figure 4-4 illustrates an 8-marker tool. The marker letters correspond to the markers' positions in the tool wiring matrix on Figure 8-2 on page 41. The markers can be divided into faces and groups as follows:

- **Faces:** The markers cannot all be seen by the Position Sensor at the same time, so this tool is divided into two faces. Markers A, B, K, and L belong to face 1; markers F, G, P, and Q belong to face 2.
- **Groups:** On each face, there are markers that are less than 50 mm apart, so the markers must be divided into two groups. One possible way to divide the tool into two groups is to put markers A, F, K, and P in group 1, and markers B, G, L, and Q in group 2. Notice that the markers in each group are evenly divided between the columns of the tool wiring matrix.

> **NOTE**
> Markers in different groups must follow the recommended minimum distance between markers specified in " Minimum Distance Between Markers" on page 14.

Figure 4-4 Groups on a Multi-Faced Tool



5 Tools and Markers

This chapter offer information about the tools and markers that can be used with NDI systems:

5.1 Passive Tools and Markers

In addition to the information provided about passive tools in Basic Concepts, which begins on page 1, the following information must be understood when designing a passive tool.

5.1.1 Marker Centre

The measured position of a marker is the centre of the marker.

When and NDI Passive Sphere is mounted on an NDI mounting post, the centre of the marker is located at the centre of the top of the mounting post. You can determine the centre of the top of the mounting post using a digitizing probe with a 1 mm diameter ball tip.

For Radix lenses, the optical center is at the top of the center of the top of the hemisphere. This is illustrated in the Radix Lens Integration Guide.

For reflective discs, the optical center is the center of the flat disc.

5.1.2 Sterilization

NDI Passive Spheres

NDI Passive Spheres can be purchased either unsterilized or sterilized.

Single-use sterile NDI Passive Spheres are available from NDI:
www.ndigital.com

NDI Radix Lenses

Radix lenses are provided unsterilized so they can be integrated into tools for subsequent sterilization. You must assess the impact of the method of sterilization on the performance, stability and suitability of the product for their intended use.

CAUTION
Do not sterilize by heat (dry or moist). These means of sterilization may result in deformation of the lens and/or compromise the reflective coating, both of which could affect tracking accuracy.

Reflective Discs

The materials used to make the disc, the reflective coating, and any additional coating will determine whether the discs can be sterilized. If the disc has additional coating, it must be kept dry so moisture does not penetrate between the coatings.

5.2 Active Tools and Markers

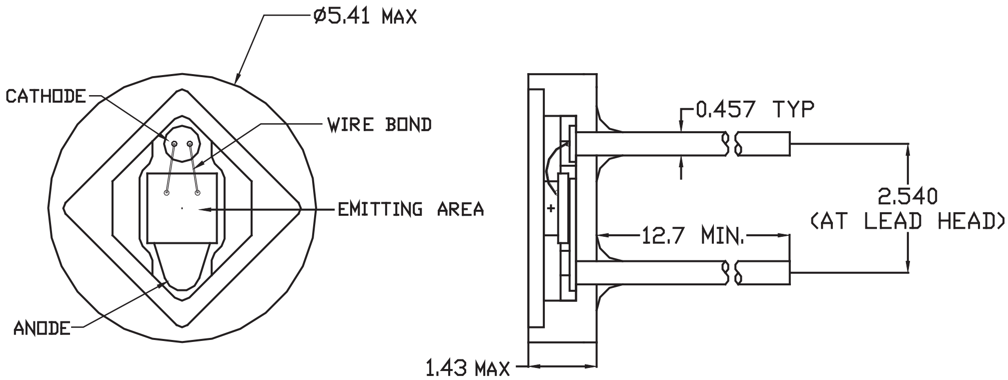
In addition to the information provided about active tools in Basic Concepts, which begins on page 1, the following information must be understood when designing an active tool.

Active markers consist of an infrared light emitting diode mounted on a ceramic base. The Position Sensor detects the infrared light emitted by the active markers. The system can report the positions of the markers individually and calculate the position and orientation of tools that incorporate them. Power for the infrared light emitting diode comes from the system control unit for active wired tools and from an external supply (such as a battery) for active wireless tools.

5.2.1 Active Marker Specifications

The appearance of the anode and cathode on the marker face depends upon the type of marker. Use the diode test function of a digital voltmeter to ensure you have correctly identified the connections. Figure 5-1 illustrates the marker components.

Figure 5-1 Standard Active Marker



5.2.2 Visible Light Emitting Diodes

Visible light emitting diodes can be incorporated into active tools to provide status information about the tool or system. For more information, see“Switches and Visible LEDs” on page 36.

5.3 Isotropic Behaviour

Markers do not behave as a perfect point source of light. As markers are viewed off-axis, the apparent centre of emission shifts. The amount of shift increases as the off-axis viewing angle is increased.

This apparent shift in the markers’ 3D locations can introduce significant errors in the tool transformations; however, you can avoid these errors by setting the maximum marker angle in the tool definition file. Once the off-axis viewing angle of a particular marker has exceeded the maximum marker angle, the system stops using data from that marker. This reduces the possibility that the system will calculate inaccurate transformations.

See “Maximum Marker Angle” on page 49 for more information on the maximum marker angle.

NOTE

With NDI Passive Spheres, as the marker is turned so that more of the mounting post comes into view, the mounting post will begin to occlude part of the marker and shift the apparent centre of emission.

6 Passive Tools

This chapter provides a number of design considerations for passive tools:

6.1 Introduction

This section covers:

- NDI Passive Sphere Mounting Posts
- Passive Tool Characterization

It is up to you to determine your own accuracy criteria and develop a protocol to ensure this accuracy can be met with your manufacturing process. NDI does not have expertise in tool manufacturing and is not familiar with unique applications.

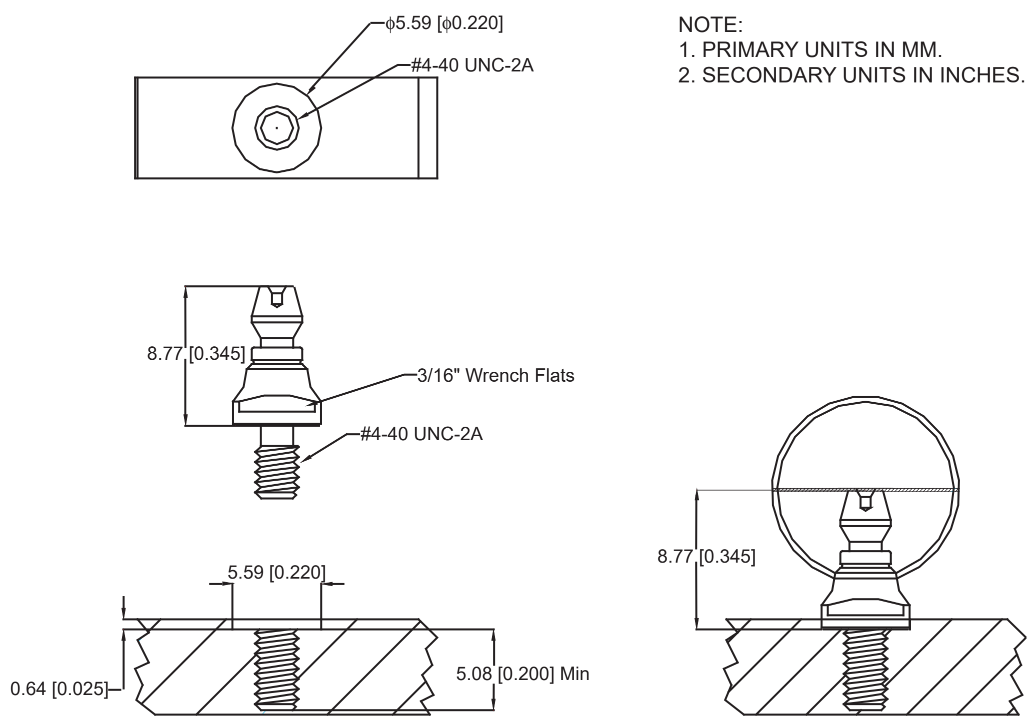
To ensure your tool is are as accurate as possible, review the information in "Tool Accuracy" on page 47.

6.2 NDI Passive Sphere Mounting Posts

A passive tool may incorporate NDI Passive Spheres, described in "Passive Tools" on page 2. The NDI mounting post for these spheres is shown in Figure 6-1 below.

The standard mounting post is designed so that the centre of a marker, when correctly fitted, is located at the centre of the top of the mounting post.

Figure 6-1 Standard Mounting Post Specifications



Custom mounting posts are available if the NDI mounting post does not meet your requirements. Contact NDI for details. Refer to "Contact Information" on page vi.

6.3 Passive Tool Characterization

To achieve the highest accuracy, NDI recommends characterizing each tool individually and creating a unique tool definition file for each tool. If this is not done (e.g. a tool definition file is reused for multiple tools, or engineering data is used to characterize a tool), the accuracy placement tolerance for the mechanical centre point of the marker must not exceed 0.05 mm.

7 Active Wireless Tools

This chapter provides a number of design considerations for active wireless tools:

7.1 Constructing an Active Wireless Tool

This section describes considerations for active wireless tool construction.

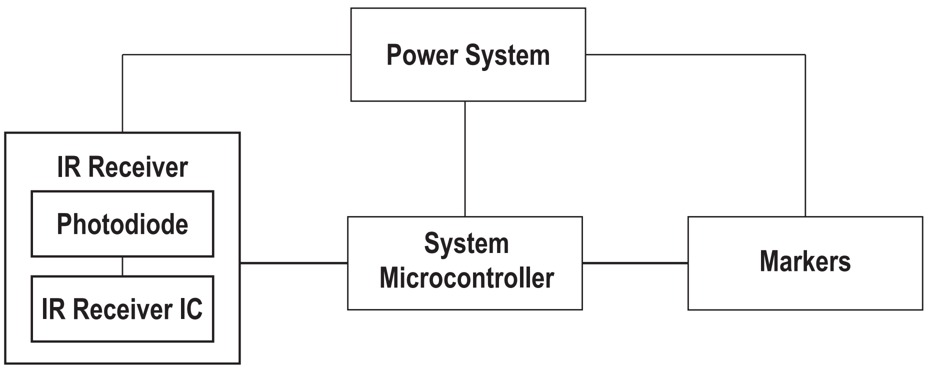
An active wireless tool is useful when a tool, for example a C-arm or a microscope, must come into contact with other equipment connected to the mains power.

Each application has its own accuracy requirements. It is up to you to determine your own accuracy criteria and develop a protocol to ensure this accuracy can be met with your manufacturing process. NDI does not have expertise in tool manufacturing, and is not familiar with each user's application to the extent of being able to make these determinations.

7.1.1 Active Wireless Tool Components

An active wireless tool has four major components: a power system, an infrared light receiver, a system micro-controller, and markers. These components are shown in the block diagram in Figure 7-1.

Figure 7-1 Block Diagram of an Active Wireless Tool



At the beginning of the active wireless tool's tracking period, the illuminators on the Position Sensor emit a short 107.3 KHz pulse of infrared light. When the infrared light receiver on the tool detects the infrared light pulse, it triggers the tool's system micro-controller to activate the active markers (and visible LEDs, if present). The Position Sensor then detects the infrared light emitted by the active markers, and calculates the position and orientation of the tool.

Power System

The power system provides power to the tool. An active wireless tool can be designed to draw power from the device to which it is connected; for example, a C-arm or a microscope. An active wireless tool can also be powered by battery; however, concerns such as sterilization, battery power, and battery life make this a less practical choice.

Infrared Light Receiver

The infrared light receiver detects the infrared light pulse from the illuminators. When the active wireless tool is in the presence of infrared light, the infrared light receiver design has the greatest effect on the tool's performance. Poor infrared light rejection could cause false firing sequences to start, or it could prevent the tool from functioning. The components used in the infrared light receiver on the NDI active wireless tool optimize the performance of the tool in the presence of infrared light.

Important characteristics of the infrared light receiver are the ability to function throughout the characterized measurement volume, and resistance to background noise. The infrared light receiver consists of a photodiode and a dedicated infrared light receiver.

Photodiode: NDI supplies a photodiode designed specifically to operate with the illuminators on the Position Sensor. The photodiode contains a bandpass filter centered at the wavelength of the illuminators, and has a very narrow response range. It is packaged in the NDI ceramic header, and can be autoclaved.

This photodiode outperforms all other photodiodes tested by NDI due to the integral bandpass filter. It is able to function correctly even when an intense infrared light source located 380 mm away is pointed directly at the device. The same source positioned at twice the distance saturated all other tested devices.

Infrared light receiver integrated circuit: The infrared light receiver integrated circuit is connected to the photodiode. The output of the infrared light receiver is buffered and fed into the system controller.

System Micro-controller

The system micro-controller controls the overall timing for the circuit. It monitors the output of the infrared light receiver, and activates the markers at the correct time. To avoid false signals caused by the markers, the micro-controller ignores the infrared light receiver output while the markers are being activated.

Markers

Active wireless tools incorporate active markers, and can also incorporate visible LEDs.

- Active markers emit infrared light. The Position Sensor detects the infrared light emitted by the active markers and uses it to calculate the position and orientation of tools that incorporate them. For more information, see “Active Tools and Markers” on page 27.
- A visible LED can be used to provide confirmation that the tool is functioning correctly; for example, the LED may be activated when the tool is within range and receiving the signal from the Position Sensor. For more information, see “Visible Light Emitting Diodes” on page 27.

8 Active Wired Tools

This chapter provides a number of considerations for active wired tool designs:

8.1 Introduction

This chapter describes the constraints and parameters related to the design of active wired tools.

Given the wide range of tools that might be constructed, it is not possible to provide specific advice on the number of markers to use or their placement. This chapter provides constraints and parameters.

Please contact NDI technical support to discuss more specific implementations. Refer to "Contact Information" on page vi.

To ensure that tools are as accurate as possible, review the information in "Tool Accuracy" on page 47.

8.2 Constraints

All active wired tools must comply with the following constraints:

- A single-faced tool has 3 to 20 markers. A multi-faced tool must have at least 3 markers per face. NDI recommends using at least 4 markers per tool or face.
- Markers must be a minimum distance apart. Refer to Table 4-1 on page 14 for the recommended minimum distances.
- Markers should be distributed as evenly as possible between columns in the tool wiring matrix. For more information, see "Tool Wiring" on page 39.
- Each tool must have a tool definition file, to describe it to the system. The tool definition file is created during the characterization process, "Characterizing a Tool" on page 62.
- The tool may optionally comply with the unique geometry constraints described in "Unique Geometry Constraints" on page 15. For a description of the differences between unique geometry tools and standard geometry tools, see Table 4-5 on page 16.

8.3 Switches and Visible LEDs

Active wired tools can be designed to include switches and light emitting diodes, which are explained below.

8.3.1 Switches

A switch on a tool can be used to trigger an action such as recording tracking data, or changing screens in the application software. Up to three switches can be incorporated into an active tool. When a switch is activated, the system sets a bit which can be read by the host computer. Switches are user-defined, and must be incorporated into the tool wiring matrix shown in Figure 8-2 on page 41.

8.3.2 Light Emitting Diodes

A visible LED on a tool can be used to indicate information about the tool or the system. For example, a visible LED could be placed on each face of a multi-faced tool, to indicate which face is being tracked.

Up to four visible LEDs can be incorporated into an active wired tool. One visible LED, the tracking LED, is reserved for use by the system; the remaining LEDs are user-defined and are controlled through your application.

A tool can have up to 20 markers, which include visible LEDs. So, if four visible LEDs are used, only 16 positions remain available for active markers. A visible LED can be specified to be the tracking LED in NDI 6D Architect.

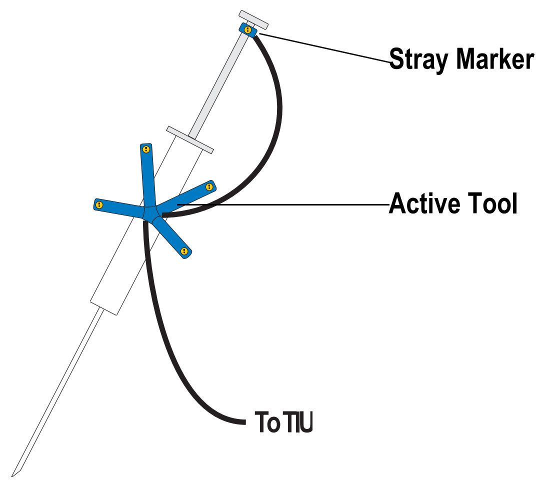
Tracking LED: This visible LED is used by the system and cannot be controlled by the API. The LED is solid on when the tool is tracking or is in the field of view of the Position Sensor (in or out of volume). The LED flashes when the system cannot detect enough markers to calculate a transformation, or when the tool is out of the field of view. Since the tracking LED is system-controlled, its behaviour will be consistent regardless of the application software used.

User-defined LEDs: User-defined visible LEDs are controlled through the application software.

8.4 Tools with Stray Active Markers

A stray marker on an active wired tool is not fixed with respect to the other markers that make up the tool. For example, a stray active marker may be used as a biopsy guide on a tracked needle, as illustrated in Figure 8-1. Only one stray marker per active tool is supported.

Figure 8-1 Biopsy Syringe with a Stray Marker



8.4.1 Stray Active Marker Characterization Settings

When characterizing a tool that incorporates a stray marker, set the following parameters:

1. Set the number of groups to 2. Assign all the markers except for the stray marker to group 1, and assign the stray marker to group 2.
2. Set the stray marker to be the last defined marker position.
3. Set the number of markers to include the stray marker.
4. Set the minimum number of markers parameter so that it does not include the stray marker.
5. In the enhanced algorithm flag parameter, logically OR the value 0x04 with the other flags. This means the enhanced algorithm flag value is 0x06 if three-marker lock-on is enabled, or 0x04 if three-marker lock-on is not enabled. The enhanced algorithm flag parameter is displayed in the tool definition information section of the main window in NDI 6D Architect. You can manually edit this value after the tool has been characterized.

8.5 Constructing an Active Wired Tool

This chapter describes some of the considerations you must use when constructing an active wired tool.

Each user has a required accuracy necessary for their own application. It is up to you to determine your own accuracy criteria and develop a protocol to ensure this accuracy can be met with your manufacturing process. NDI does not have expertise in tool manufacturing, and is not familiar with each user's application to the extent of being able to make these determinations.

This section covers:

- "Electrical Safety Considerations" on page 38
- "System Control Unit and Strobers (Hybrid Spectra System)" on page 39
- "Tool Wiring" on page 39
- "Tool Cables" on page 42

8.5.1 Electrical Safety Considerations

It is beyond the scope of this document to describe all the electrical safety issues associated with tool design. Furthermore, the Position Sensor is only one component in the overall system — safety considerations must also be applied to the workstation, computer peripherals, isolation transformer, the suite of tools, and all other components of this system. It is the responsibility of the OEM to test and certify that the entire system complies with the necessary safety standards.

The Vega and Spectra systems have been designed to be compatible with the medical safety standard IEC 60601. The tools are treated as F-Type Isolated (Floating) Applied Parts (Type BF). For this safety rating to apply, you must ensure that the tool design will maintain the isolation from electronic circuitry within the tool to objects that the tool may be expected to contact during its normal use.

To ensure that your tool design complies with all relevant electrical safety standards, remember the following:

1. Work with an approval agency qualified in testing medical standards. Consult with the necessary safety approval agencies to obtain advice and guidance specific to a particular design.
2. Consult and comply with the following standards:
   - **IEC60601-1** Medical electrical equipment - Part 1: General requirements for safety
   - **IEC60601-1-1** Medical electrical equipment - Part 1-1: General requirements for safety - Collateral standard: Safety requirements for medical electrical systems
   - **IEC60601-1-2** Medical electrical equipment - Part 1-2: General requirements for safety - Collateral standard: Electromagnetic compatibility - Requirements and tests

   > It is not straightforward to interpret the IEC 60601 standard as it applies to active tools, especially when these tools are connected to other electro-medical devices such as a surgical microscope or bipolar coagulating forceps. NDI recommends that you involve experts from the necessary safety approval agencies at the onset of the development project. This early involvement can help avoid an expensive re-design of the tool in order to comply with requirements of the medical standards.

3. Consult and comply with additional applicable national standards and amendments.
4. The Vega and Spectra systems are designed for Type BF applied parts only.

8.5.2 System Control Unit and Strobers (Hybrid Spectra System)

The System Control Unit (SCU) has three tool ports and one GPIO port suitable for connection to Type BF (body floating) applied parts; however, these four ports are not isolated from one another. You must take into account this lack of inter-port isolation when considering limits on patient auxiliary leakage currents (i.e. leakage current between tools in contact with a patient.) The lack of isolation between these ports also requires that when you are designing a tool or GPIO device intended to be attached to other pieces of equipment (e.g. surgical microscope), you must consider isolation of the tool/GPIO device from that equipment such that the isolation between a patient (connected to another tool port via a Type BF tool), and earth-ground and/or mains is preserved. If any one tool port or GPIO port's isolation is violated, then all four port isolations are violated.

The SCU also has an expansion port that is suitable for connection to a strober. A second strober can be connected to the first strober. Each strober allows up to three additional Type BF tools and one GPIO device to be connected to the system. This expansion port is electrically isolated from the tool ports and GPIO port on the SCU, so tools connected to the strobers are electrically isolated from those connected to the SCU. This allows users to configure their system to track equipment (e.g. surgical microscope) and patient applied parts simultaneously, by connecting equipment tools to one device (e.g. SCU tool port) and patient applied parts to the other (e.g. strober). Note that the tool ports and GPIO port on the strobers are not isolated from one another.

To avoid electrical shock to a patient, make sure that all tools that come into contact with the patient are electrically isolated. To maintain tool isolation, tools that come into contact with other equipment connected to the mains power must be connected to a separate tool port device from patient-applied tools, or use proper isolation techniques such as isolation blocks. To avoid isolation concerns, a passive or active wireless tool may be a more appropriate choice for a tool that comes into contact with other equipment.

If necessary, consult the Standards (IEC60601-1, IEC60601-1-1 and any applicable national differences and amendments and any applicable particular standards) and your regulatory agency representative for assistance in tool electrical safety design.

8.5.3 Tool Wiring

Do not use soldering temperatures above 260° C or allow contact for longer than 10 seconds when soldering ceramic markers. These conditions may damage the ceramic marker.

When designing an active wired tool, you will need to choose the number and location of markers that is best suited to your application. Each active tool has a serial read only memory (SROM) device to store the tool definition file. You will need to consider the location of the SROM device and how the tool will be recognized by the System Control Unit. The best location for the SROM device is inside the circular plastic connector (instead of in the tool body) to reduce the possibility of signal loss. For the tool to be recognized by the System Control Unit, the diode (D1 in the tool wiring matrix) must be located in row 1 and must be connected to the field effect transistor (see Figure 8-2 on page 41).

Consider your sterilization requirements when choosing components.

Tool Wiring Matrix

The IREDs on an active tool are connected in a 4×5 matrix, as shown in Figure 8-2 on page 41. Individual markers may be turned on by energizing the appropriate row and column. Multiple markers may be activated by supplying power to multiple rows and/or columns.

For optimal power, markers that will be activated on at the same time (markers in the same group, on the same face) should be distributed across different columns in the tool wiring matrix.

Example - Wiring a Four-Marker Tool

An optimal way to wire a four-marker tool would be to use A, G, M and S in the tool wiring matrix. This way, the markers are distributed evenly across the columns of the tool wiring matrix, so the markers are powered evenly.

A less favourable way to wire a four-marker tool would be to use A, G, M and B in the tool wiring matrix. In this case, markers A and B are in the same column of the tool wiring matrix, and so would be significantly less bright than markers G and M. Polaris marker detection is based on the brightness of the brightest marker, so the system may have difficulty detecting the weaker markers.

Example - Wiring a Six Marker Tool

An inefficient way to wire the tool would be A, B, C, D, E, F. Since marker F is the only one in a column by itself, the A, B, C, D, and E markers would be weaker than F. Polaris marker detection is based on the brightness of the brightest marker, so the system may have difficulty detecting the weaker markers.

A better wiring would be A, F, K, B, G, L. Not all columns in the wiring matrix are used, but the markers are distributed evenly across the columns that are used, so all markers will have roughly the same brightness.

Example - Wiring a Five Marker Tool

There is no way to distribute five markers evenly among four columns. Various tool designs that place two markers in some columns and one marker in others are equivalent.

Figure 8-2 Tool Wiring Matrix

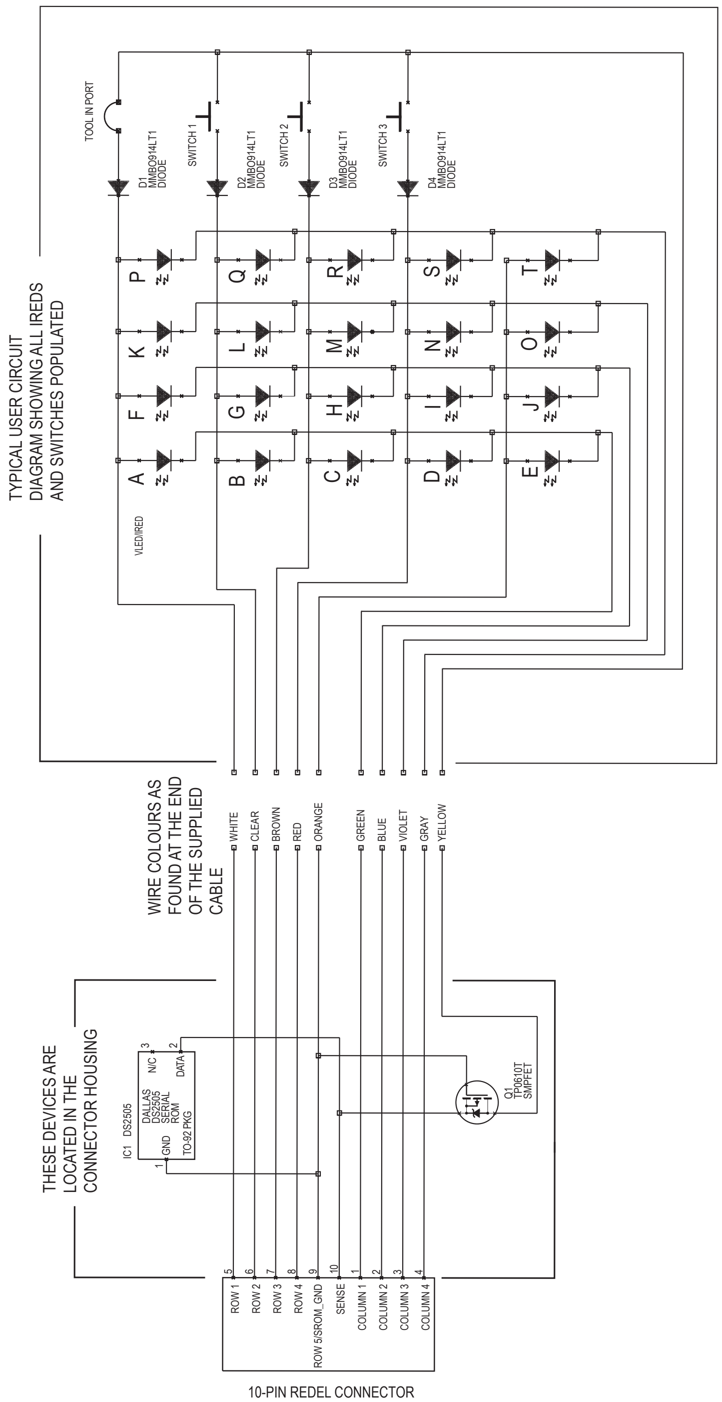
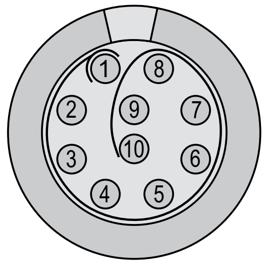


Figure 8-3 Tool Connector Pin Orientation -Viewed From Rear



8.5.4 Tool Cables

Tool cables and cable assemblies are available from NDI. The tool cable assembly wiring is shown in Figure 8-2 on page 41. The connector in NDI's tool cable assembly is not suitable for autoclaving.

If you are considering using a different cable, there are many criteria that you must consider when selecting the cable. Many of these criteria are specific to the design and application and must be formulated by the designer. Two important criteria that must be considered in all applications are wire size and wire length.

The resistance of the wire used in the tool cable has an appreciable effect on the optical output power of the active marker. This resistance should be kept reasonably uniform across tool designs to ensure that the output power for the active markers will be approximately constant. The resistance of the wire from the tool connector to an individual active marker and back to the connector should be less than or equal to 1.50 Ω.

For example, suppose you wish to use a 26 gauge wire (65 strands of 44 gauge tinned copper) with a resistance of 44.1 Ω per 1000 feet. To calculate the maximum length of a cable that will have a total path resistance of 1.50 Ω, use:

$$2 \times \text{length} = \frac{1.5\Omega}{\left[\frac{44.1\Omega}{1000\ \text{feet}}\right]}$$

Thus, maximum cable length = 17.0 feet (5.18 m).

9 Tool Tip Offset

This chapter describes two methods for determining the tool tip offset:

9.1 Introduction

When the system tracks a tool, it reports the transformations of the origin of the tool. In certain circumstances, it is useful to track a point on the tool other than the tool's origin. In particular, it is useful to track the location of the tip of a probe. It is possible to define the tool's origin at the tip of the probe; however, if the tool is later bent, the origin will no longer be located at the tip.

NDI recommends determining the tool tip offset (the vector between the tip of the tool and the origin of the tool) prior to each use. Application software can apply the tool transformations to the tool tip offset in order to determine the location of the tool tip.

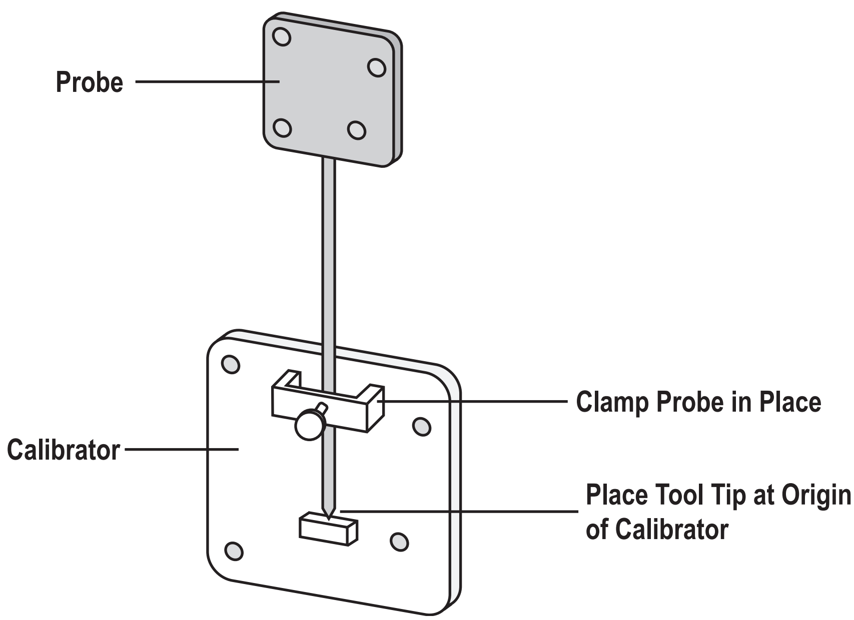
Determining the tool tip offset prior to each use ensures that the location of the tool tip is known as accurately as possible.The tool tip offset can be determined in two different ways:

- Calibrator
- Pivoting

9.2 Calibrator

A calibrator is a rigid body made up of three or more markers. It incorporates a clamping mechanism to allow another tool (usually a probe) to be clamped into place. An example of a calibrator is illustrated in Figure 9-1.

Figure 9-1 A Calibrator Tool



To use a calibrator to determine the tool tip offset of a probe, clamp the probe in place on the calibrator. The origin of the calibrator is defined at the point where the tool tip will rest, or at some known distance from it. The system can then measure the positions of the origin of the probe and the origin of the calibrator. The application software compares these measurements to determine the tool tip offset of the probe.

Calibrator Design Considerations

- The calibrator must follow the tool constraints outlined in the appropriate section:

    - "Passive Tools" on page 29
    - "Active Wireless Tools" on page 32
    - "Active Wired Tools" on page 35
- The calibrator must have a groove in which the probe shaft will sit.
- The calibrator must have a clamp, to hold the probe in place in the groove. The probe must be held securely so that it will not move during the calibration data collection.

9.3 Pivoting

You can determine the tool tip offset by pivoting, using either NDI ToolBox or NDI 6D Architect software. During the pivoting procedure, the system will measure the positions of the markers while you pivot the tool. The software collects this data, and uses it to determine the tool tip offset. If the tool has a ball tip, the tool tip offset represents the offset from the origin of the tool to the centre of the ball. If the tool has a sharp tip, the tool tip offset represents the offset from the origin of the tool to the tip of the tool.

A pivot block with an appropriately sized divot must be used to ensure that the pivoting procedure is accurate and repeatable.

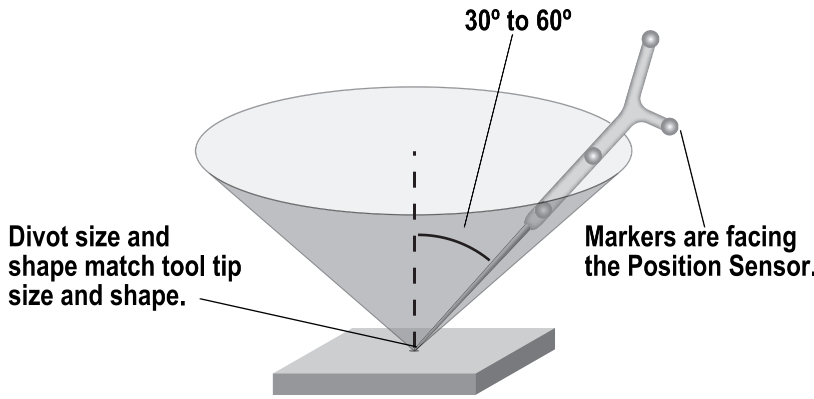
Pivot Block Design Considerations

- The pivot block must be manufactured with substantial mass, to reduce the possibility of movement during use.
- It must be possible to securely clamp the pivot block.
- The pivot block must incorporate a divot, in which to pivot a tool. The size and shape of the divot must match the tool tip, to ensure that the tip does not move. For example, a probe with a 1 mm ball tip should have a hemispherical divot with a 1 mm diameter.
- A shallow divot must be provided for probe tools with sharp points.
- The pivot block may incorporate an appropriately sized convex arrangement (ball), to accommodate tools with concave tips.

Pivoting Technique

1. Rest the tool tip in the divot in the pivot block. The size and shape of the divot must match the tool tip, to ensure that the tip does not move.
2. Pivot the tool in a cone shape, at an angle of 30° to 60° from the vertical, as shown in Figure 9-2.
    - Keep the tool tip stationary, and ensure that there is a line of sight between the markers on the tool and the Position Sensor throughout the pivoting procedure.
    - Pivot the tool slowly for about 20 seconds.

Figure 9-2 Pivot Technique



10 Tool Accuracy

This chapter contains information for improving the accuracy of the tool you are designing:

10.1 Introduction

This chapter describes some of the factors that affect tool accuracy:

- Marker Geometry
- Tool Tracking Parameters
- Estimating Tool Accuracy
- Marker Occlusion Issues

10.2 Marker Geometry

In general, the following may improve the accuracy of the returned tool transformations:

- **Increasing the number of markers:** Increasing the number of markers on a tool may improve the accuracy of the returned tool transformation, since it decreases the effect of each individual marker. Thus, if a marker is measured inaccurately (for example, if it is partially occluded), its effect will be minimized if there are a large number of markers.
- **Increasing the 2D or 3D spread of the markers:** Increasing the distance between markers minimizes the effects of the error introduced by any one marker.
- **Decreasing the distance from the markers to the tool tip:** The shorter the distance from the markers to the tool tip, the smaller the extrapolation error.
- **Designing the tool so that the user can use it without occluding any markers:** Occluding markers can lead to the tool going missing if not enough markers are in view. It can also lead to less accurate transformations, due either to fewer markers being used in the calculations, or to a measured marker position being shifted from the actual marker position if the marker is only partially occluded. See “Marker Occlusion Issues” on page 58 for details on the effects of marker occlusion.
- **Create individual tool design files (.rom file):** Characterize the marker positions on each tool individually instead of relying on a generic tool design file.

10.3 Tool Tracking Parameters

While tracking a tool, the system uses the tool tracking parameters to determine which markers to use to calculate a tool transformation, and when to report tool transformations. The tool tracking parameters are stored in the tool definition file for a tool, and are set when the tool is characterized. The flowchart on page 56 describes how the system uses the tool tracking parameters.

> **i** Two physically identical tools using different parameters can have significantly different accuracy performance, so it is important to carefully consider the effects of the tool tracking parameters.

The tool tracking parameter values limit the magnitude of the RMS error returned with each transformation. This error is a measure of how well the system was able to fit the measured marker positions to the marker geometry specified in the tool definition file. Undesirably high RMS errors indicate that the tool tracking parameters were not set appropriately.

The tool tracking parameters are:

- maximum 3D error (explained on page 49)
- maximum marker angle (explained on page 49)
- minimum number of markers (explained on page 51)
- minimum spread (explained on page 53)

10.3.1 Maximum 3D Error

The maximum 3D error parameter specifies, in the tool definition file, the maximum allowable 3D error for each marker on a tool. The 3D error is the difference between the measured and expected location of a marker on a tool. The expected location of a marker on a tool is specified in the tool definition file.

How the system uses the maximum 3D error: The system calculates an initial estimate for the tool transformation. It then performs a calculation to minimize the distance between the measured 3D position of each marker and the expected 3D locations as given in the tool definition file. A measure of this minimization is the RMS error reported with each transformation. The minimized distance for each marker is the 3D error. If the 3D error for a particular marker is greater than the specified maximum 3D error value, the system will recalculate the tool transformation without the data from that marker.

How the maximum 3D error improves tool accuracy: The maximum 3D error parameter prevents the system from using potentially inaccurate data to calculate a tool transformation. For example, if a marker becomes partially occluded, the apparent centre of the marker will shift, which will cause an error in the measured position of the marker. This error, in turn, will increase the error in the calculated tool transformation. Setting a maximum 3D error causes the system to stop using the marker data once the 3D error has reached a certain level, reducing the possibility that the system will calculate inaccurate transformations.

Setting the maximum 3D error: The value for the maximum 3D error parameter must strike a balance between rejecting outlier marker measurements (e.g. when the marker is partially occluded) and not rejecting valid marker measurements that will contribute to the accuracy of the tool transformations. The system can measure a marker throughout the characterized measurement volume with a particular accuracy; the 3D error parameter value must be set higher than the RMS accuracy of the system:

- **Vega (all models):** 0.12 mm RMS (pyramid volume), or 0.15 mm RMS (extended pyramid volume
- **Spectra:** 0.25 mm RMS (pyramid volume), or 0.30 mm RMS (extended pyramid volume)
- **Vicra:** 0.25 mm RMS

The maximum 3D error can be set in NDI 6D Architect, and by default is set to 2 mm.

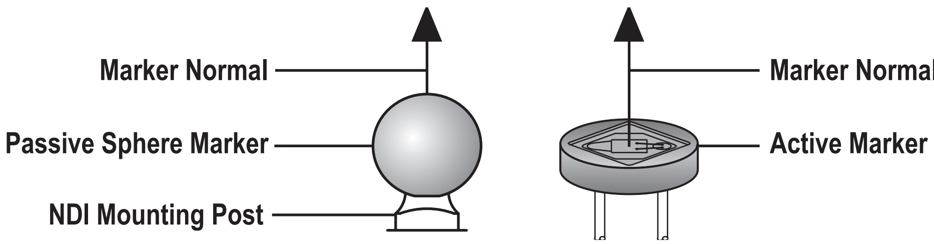
10.3.2 Maximum Marker Angle

The maximum marker angle parameter specifies, in the tool definition file, the maximum allowable angle between a marker and each of the two sensors in the Position Sensor.

How the system uses the maximum marker angle:

Each marker in the tool definition file has an associated normal vector. A marker normal is a vector of length 1, and points in the same direction as the marker (see Figure 10-1).

Figure 10-1 Markers with Marker Normals

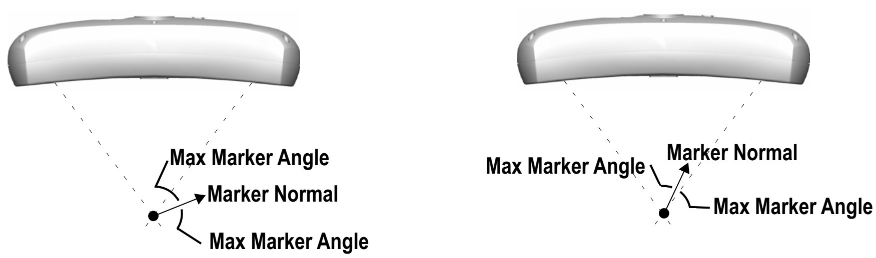


The system uses the marker normal to determine which direction the marker is facing. The system measures the angle between the marker normal and each sensor, in both the Position Sensor's *xy*- and *yz*-planes. (The Position Sensor's coordinate system is described in the user guide that accompanied your system.) If the angle between the marker normal and either sensor is greater than the specified maximum marker angle value, the system will not use the data from that marker to determine the tool transformation.

In the diagram at the **left side** of Figure 10-2, the angle between the marker normal and the left sensor is greater than the maximum marker angle. Therefore, the system would not use this marker to calculate a transformation.

In the diagram at the **right side** of Figure 10-2, the angle between the marker normal and each sensor is less than the maximum marker angle. Therefore, the system could use this marker to calculate a transformation.

Figure 10-2 Maximum Marker Angle



How the maximum marker angle improves tool accuracy: Markers (particularly active markers) do not behave as a perfect point source of light. As markers are viewed off-axis, the apparent centre of emission shifts. The amount of shift increases as the off-axis viewing angle is increased. This apparent shift in the markers' 3D locations can introduce significant errors in the tool transformations. Setting a maximum marker angle causes the system to stop using the marker data once the off-axis viewing angle has reached a certain level, reducing the possibility that the system will calculate inaccurate transformations.

Setting the maximum marker angle: When setting the maximum marker angle, consider whether markers might occlude each other. Often, a tool will stop tracking due to partial marker occlusion before the markers exceed the maximum marker angle. See "Marker Occlusion Issues" on page 58 for details.

The maximum marker angle can be set in NDI 6D Architect. The default maximum marker angle is ±90° for an NDI Passive Sphere, and ±60° for an active marker. The value in NDI 6D Architect is the half-range, i.e. a value of 90° in NDI 6D Architect is actually ±90°.

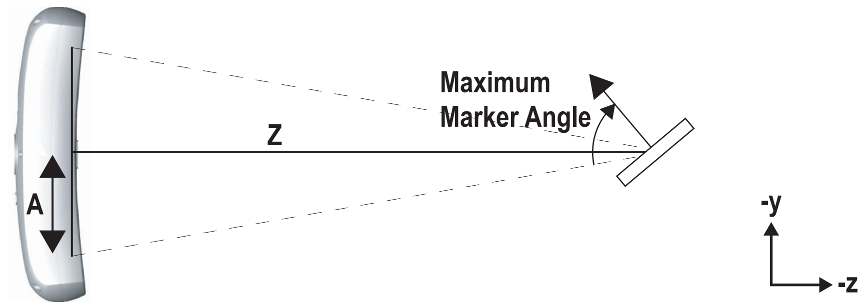
Example - Determining the Actual Half-Range of Use

The closer a marker is to the Position Sensor, the smaller the angle it can be turned and still be within the maximum marker angle.

To determine the actual half-range of use, consider Figure 10-3. Z is the distance from the Position Sensor along the *z*-axis, and A is half the distance between sensors. The actual half-range of use will be the maximum marker angle reduced by the angle formed at the apex of the triangle with these two segments. This angle is equal to the inverse tangent of A over Z. Thus:

$$\text{actual half range} = \text{maximum marker angle} - \operatorname{atan}\left(\frac{A}{Z}\right)$$

Figure 10-3 Determining the Actual Half-Range of User



The length A is approximately 250 mm (Vega and Spectra), 100 mm (Vicra).

Table 10-1 and Table 10-2 list some examples of the actual half range of usage for different marker types. The active marker calculations assume a maximum marker angle of ±60º; the passive marker calculations assume a maximum marker angle of ±90º.

Table 10-1 Actual Half-Range of Tool Use at Various Depths - Vega and Spectra

Distance From Position Sensor (Along *z*-axis)	Half Range of an Active Marker	Half Range of a Passive Marker
1500 mm	50.5º	80.5º
1900 mm	52.5º	82.5º
2400 mm	54.0º	84.1º

Table 10-2 Actual Half-Range of Tool Use at Various Depths - Vicra

Distance From Position Sensor (Along *z*-axis)	Half Range of an Active Marker	Half Range of a Passive Marker
557 mm	49.8º	79.8º
810 mm	53.0º	83.0º
1063 mm	54.6º	84.6º

10.3.3 Minimum Number of Markers

The minimum number of markers parameter specifies, in the tool definition file, the minimum number of markers that the system must use in the calculation of a tool transformation.

How the system uses the minimum number of markers: If the system cannot calculate a transformation using the minimum number of markers, it will report that the tool is missing. The system may not be able to use the minimum number of markers, for example, if some of the markers are outside of the characterized measurement volume, are past the maximum marker angle, are occluded, or have exceeded the maximum 3D error.

How the minimum number of markers improves tool accuracy: When the system calculates a transformation, it minimizes the overall error by fitting the measured marker positions, as closely as possible, to the marker geometry specified in the tool definition file. A measure of this minimization is the RMS error reported with each transformation.

Consider the case where one or more of the markers used in the transformation is inaccurate (for example, the marker is partially occluded). The system will calculate a transformation while minimizing the overall error. Although this fit may reduce the individual marker 3D errors so that they lie within acceptable tolerances, it may also result in an error in the transformation.

Increasing the minimum number of markers reduces the effect of a single marker on the accuracy of a transformation. This is due to the fact that with more markers, the system will have more constraints when fitting the measured marker positions to a tool transformation if one of the markers is measured inaccurately. Thus, in general, more markers used to calculate a transformation results in a higher accuracy.

Setting the minimum number of markers causes the system to not report transformations when too few markers have been used in the calculation, reducing the overall error in reported transformations.

Setting the minimum number of markers: NDI recommends that the minimum number of markers be set to no less than four. If the minimum number of markers is set to three, the following situation can occur: suppose the system can detect three markers on a tool, and one measured marker position is shifted from the marker's actual position (due to a partial occlusion, for example). The three measured marker positions are still coplanar (since three markers are always coplanar), and so will then be fitted to an incorrect plane, which can significantly decrease the accuracy of the transformation.

If a tool is not designed to be a linear (5DOF) tool, the minimum number of markers must be greater than the greatest number of collinear markers on the tool.

When setting the minimum number of markers parameter value, consider the performance of the tool for all possible combinations of that number of markers. "Tool Accuracy" on page 47 explains how to estimate tool accuracy of a probe tool. If specific combinations of markers result in a subsequent tool transformation accuracy that is unacceptable, consider the following courses of action:

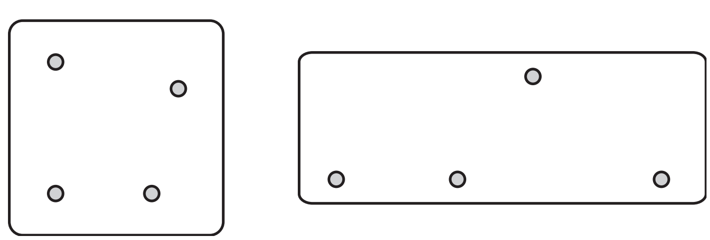
- Re-design the marker geometry to eliminate this worst-case geometry.
- Increase the minimum number of markers parameter value.
- Make use of the minimum spread parameters (described on page 53) to automatically reject particularly poor marker geometries.

The minimum number of markers parameter can be set in NDI 6D Architect.

Setting the Minimum Number of Markers

Two four-marker planar tools are shown in Figure 10-4.

Figure 10-4 Setting the Minimum Number of Markers



Consider the tool on the left. A 6DOF transformation will be returned whether the minimum number of markers is set to either three or four. If the parameter is set to four, the transformations will be more accurate; however, if one marker is not used in the transformation (for example, if the marker is occluded) then the tool will be reported as missing.

Now consider the tool on the right. Three of the markers are collinear. In order to get a 6DOF transformation, you have two options:

- Set the minimum number of markers to four. If one marker is not used in the transformation (for example, if the marker is occluded) then the tool will be reported as missing.
- Set the minimum number of markers to three, and use the minimum spread parameters (described on page 53) to prevent the system from returning a transformation that does not include the top marker. The spread parameters may be set such that one of the three collinear markers could be missing, and a transformation could still be returned.

10.3.4 Minimum Spread

The three minimum spread parameters specify, in the tool definition file, the distance, area, or volume that the markers used in the calculation of a tool transformation must cover. That is, the spread parameters specify how much the markers need to be spread out.

How the system uses the minimum spread: Once the system has determined a final estimate for the tool transformation, it performs a marker spread check. The marker spread check calculates the minimum distance, area, or volume that would contain all the markers used to obtain this solution. It compares this result to the specified Minimum Spread 1, Minimum Spread 2 and Minimum Spread 3 parameters. If the space containing the markers used in the transformation is smaller than the space specified by the spread parameters, the system will not return the tool transformation. Table 10-3 describes how the system carries out the marker spread check for various values of the spread parameters.

Table 10-3 Marker Spread Check for Various Values of the Minimum Spread Parameters

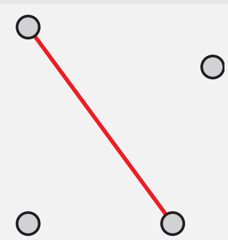
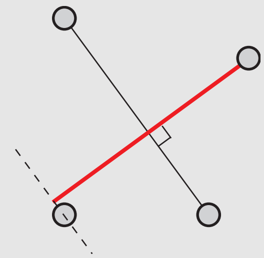
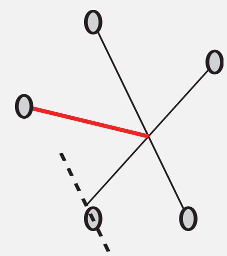
Minimum Spread Parameter Values	Resulting Marker Spread Check	Example
Min. spread 1 = 0	The marker spread check is disabled.	
Min. spread 1 = non-zero Min. spread 2 = 0 Min. spread 3 = 0	The system performs a one-dimensional marker spread check. In order for the system to report the transformation: The longest segment length (distance between two markers) on the tool must be greater than the value of minimum spread 1.	

Table 10-3 Marker Spread Check for Various Values of the Minimum Spread Parameters

Minimum Spread Parameter Values	Resulting Marker Spread Check	Example
Min. spread 1 = non-zero Min. spread 2 = non-zero Min. spread 3 = 0	The system performs a two-dimensional marker spread check. In order for the system to report the transformation: The largest segment length (distance between two markers) on the tool must be greater than the value of minimum spread 1. The largest vector perpendicular to the first segment must have magnitude greater than the value of minimum spread 2.	
Min. spread 1 = non-zero Min. spread 2 = non-zero Min. spread 3 = non-zero	The system performs a three-dimensional marker spread check. In order for the system to report the transformation: The largest segment length (distance between two markers) on the tool must be greater than the value of minimum spread 1. The largest vector perpendicular to the first segment must have magnitude greater than the value of minimum spread 2. The largest vector perpendicular to the first two must have magnitude greater than the value of minimum spread 3.	

How the minimum spread improves tool accuracy: In general, the accuracy of tool transformations is improved by increasing the 2D or 3D distribution of markers on the tool. Setting the minimum spread parameters causes the system to only report transformations that include markers spread over a certain area or volume, improving the accuracy in reported transformations.

Setting the minimum spread parameters: Consider all possible marker geometries made up of the minimum number of markers, and set the spread parameters to reject poor marker geometries. Poor marker geometries might include, for example, collinear markers.

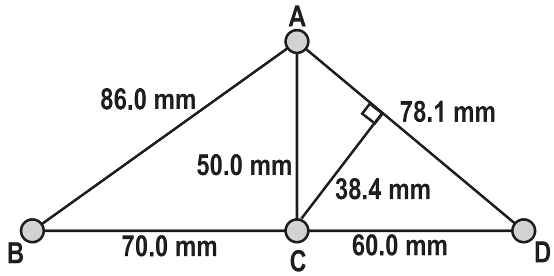
For a linear (5DOF) tool, spread parameters 2 and 3 must be set to zero, because the tool is one-dimensional. For a planar tool, spread parameter 3 must be set to zero, because the tool is two-dimensional.

The minimum spread parameters can be set in NDI 6D Architect.

Setting the Minimum Spread Parameters

The tool in Figure 10-5 shows a four-marker planar tool, with all the segment lengths labeled. Markers B, C, and D are collinear.

Figure 10-5 Four-Marker Planar Tool

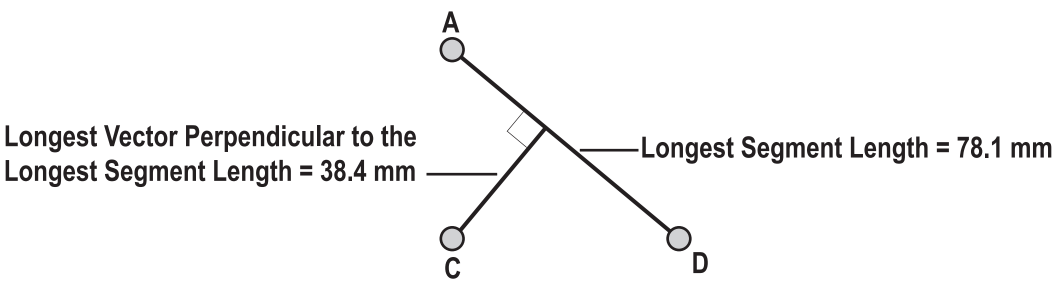


Consider the case where the minimum number of markers for this tool is set to three. The system will still return transformations even if one of the markers is not used to calculate the transformation (for example, if it becomes occluded). If, however, marker A is not used in the transformation, the tool becomes a linear (5DOF) tool. To avoid this possibility, the spread parameters can be set to make sure that transformations that do not include marker A are not reported.

Minimum spread 1 and minimum spread 2 must be set to non-zero values.This makes the system carry out a two-dimensional spread check, which will fail if marker A is not used.

To determine the values of marker spread 1 and marker spread 2, consider the smallest marker geometry that includes marker A but excludes one of the other markers. This is the case in which the system does not use marker B to calculate the tool transformation, as show in Figure 10-6.

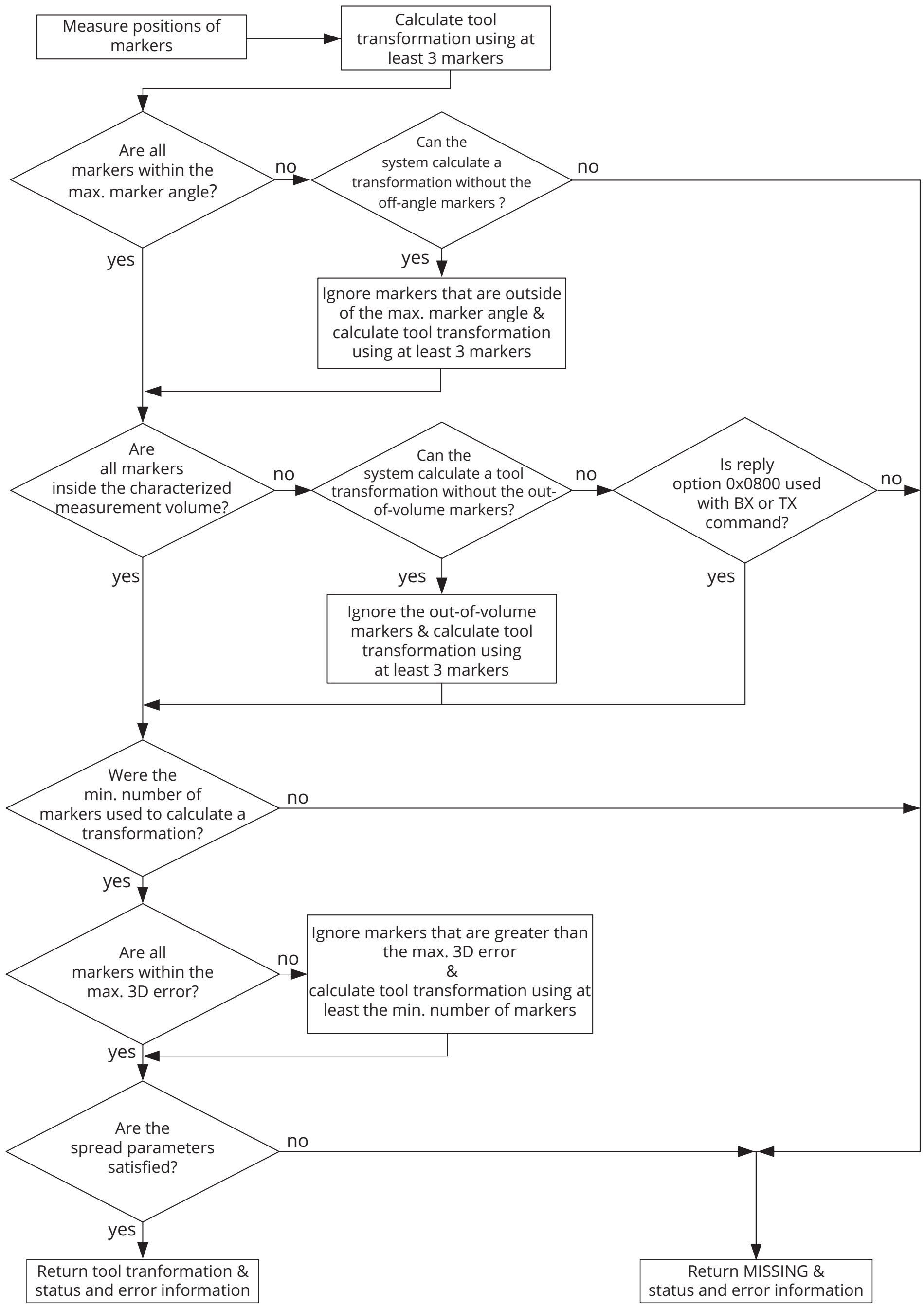
Figure 10-6 Minimum Spread Parameter



Thus, to allow for any one of the markers except marker A to be discarded, the spread parameters can be set to:

minimum spread 1 = 77
minimum spread 2 = 37.5
minimum spread 3 = 0

Figure 10-7 How the System Uses the Tool Tracking Parameters



10.4 Estimating Tool Accuracy

Refer to the user guide that accompanied your system for information on the RMS accuracy of your system. The actual accuracy of your system also depends on tool design.

10.4.1 Estimate Tool Accuracy

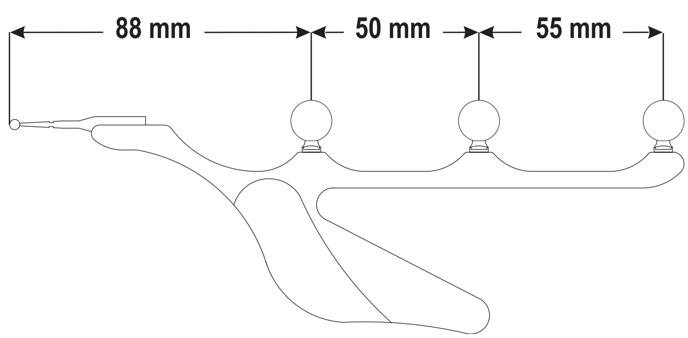
For a system that measures markers with an accuracy of *x* mm:

- If the tool has a point of interest (such as a probe tip) whose location will be calculated using application software, consider the maximum amount that point of interest could move while all the markers stay within *x* mm of their original positions.
- Be sure to estimate the accuracy of the tool for every combination of markers that fits the minimum number of markers and minimum spread parameter values that you intend to use in the tool definition file. If some combination of these markers leads to an undesirably high error, you should consider changing the parameter values or redesigning the tool.

Estimating the Accuracy of a Linear Probe

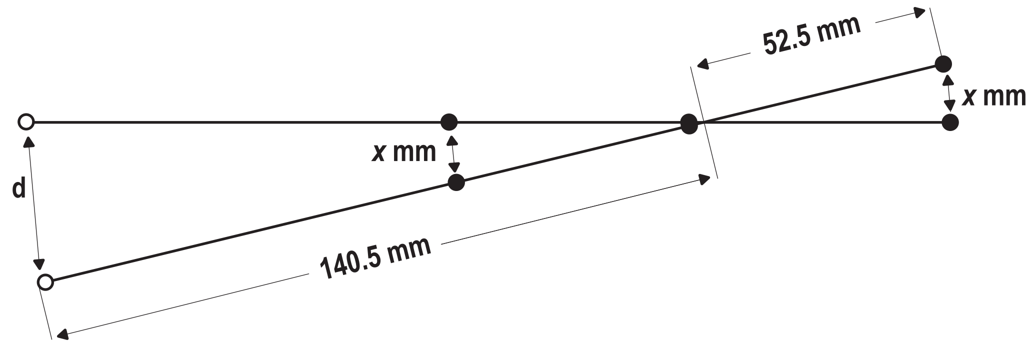
To estimate the accuracy of the linear probe tool in Figure 10-8, consider the maximum distance the probe tip could move while all the markers stay within *x* mm of their original positions (where *x* is the value you chose for the maximum 3D error in the tool definition file).

Figure 10-8 Linear Probe



The worst-case scenario for the probe in Figure 10-8 is the case where the system reports the location of each of the end markers as being ±*x* mm from their actual position, in such a way that the reported position of the tool is rotated from its actual position about a point halfway between the end markers, as shown in Figure 10-9.

Figure 10-9 Estimating the Accuracy of a Linear Probe



The tool accuracy can be estimated by determining how far the reported tool tip location is from its actual location. This is distance **d** in Figure 10-9. The triangles on either side of the point of rotation in Figure 10-9 are proportional, so distance **d** can be determined using ratios: $\frac{\mathbf{d}}{140.5} = \frac{x}{52.5}$.

For example, consider a maximum 3D error value of 0.6 mm. In this case, *x* = 0.6, so **d** = 1.6 mm. In the worst-case scenario, the reported probe tip location could differ from the actual probe tip location by as much as 1.6 mm.

A tool design which allows the most accurate tool tip offset has a large distance between markers along the tool's axis, and a short distance between the tool tip and the markers.

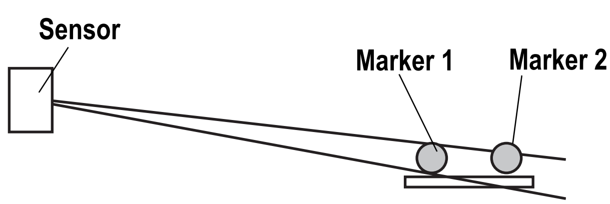
10.5 Marker Occlusion Issues

This section discusses the effects of markers occluding each other, and offers some design suggestions to avoid marker occlusion.

10.5.1 What is Marker Occlusion?

Marker occlusion occurs when a marker is blocked (entirely or partially) from view of one or both of the sensors in the Position Sensor. This section deals with the specific situation where one marker occludes another marker. This type of marker occlusion occurs when two markers are approximately aligned with one of the sensors, as illustrated in Figure 10-10.

Figure 10-10 Marker Occlusion



When one marker partially occludes another, the markers appear to the sensor as though the infrared light sources are merged, as shown in Figure 10-11.

Figure 10-11 Sensor Image of Partially Occluded Marker

Marker occlusion occurs more often with NDI Passive Spheres than active markers, because passive markers are larger and viewable from all sides, whereas active markers are usually flush with the tool surface. In general, a passive tool will stop tracking due to partial marker occlusion before the markers exceed the maximum marker angle.

10.5.2 Effects of Marker Occlusion

When one marker partially occludes another marker, either of the following results could occur:

- The system does not interpret the merged infrared light spots as being a valid marker. This results in one or both markers not being used to calculate the transformation.
- The system interprets the merged infrared light spots as being one of the markers. This results in the measured position of the marker being offset from the actual position of the marker. This offset may or may not exceed the maximum 3D error parameter value.

The end result of the above situations can be one of the following:

- The system reports the tool as missing, because not enough markers were used to calculate the transformation.
- The system returns a transformation with an increased overall error, because one of the markers used in the transformation was partially occluded, and the measured position of this partially occluded marker was offset from its actual position.

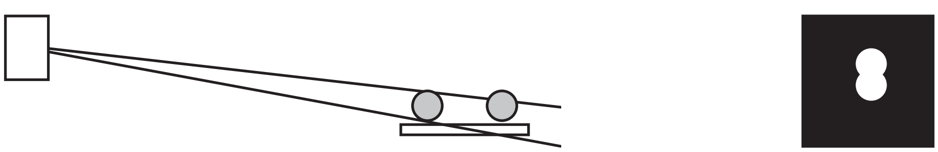
10.5.3 How to Avoid Marker Occlusion - Possible Solutions

A possible solution to avoid marker occlusion is to design the tool in such a way that it is not possible for the markers to occlude one another.

Example 1

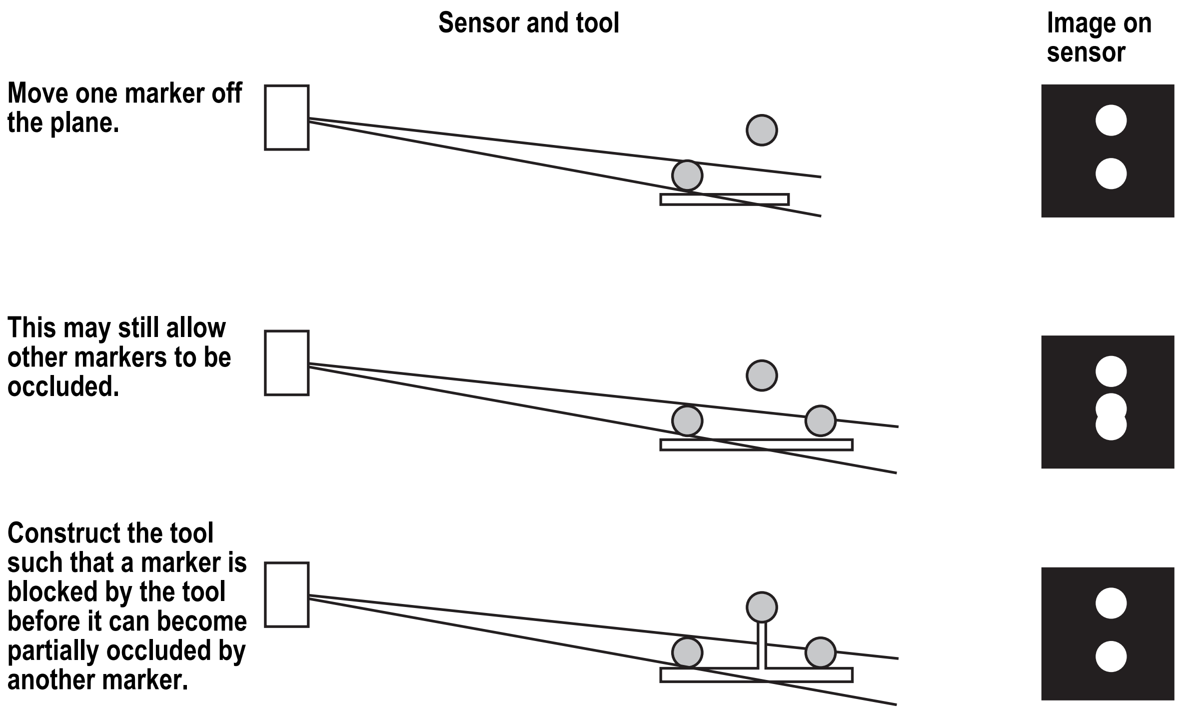
Consider the following planar tool. Figure 10-12 illustrates the side view and the sensor image view of a partial occlusion.

Figure 10-12 Marker Occlusion - Side View and Sensor Image



We can attempt to eliminate the occlusion by trying the following solutions:

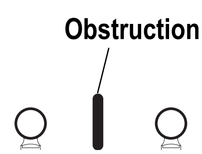
Figure 10-13 Eliminating Marker Occlusion



Example 2

It is possible to build a tool such that there is an obstruction between every pair of markers, as illustrated in Figure 10-14. This obstruction will block the rear marker before it becomes occluded by the front marker. This eliminates the problem of one marker partially occluding another marker and resulting in a sensor image of merged infrared light sources.

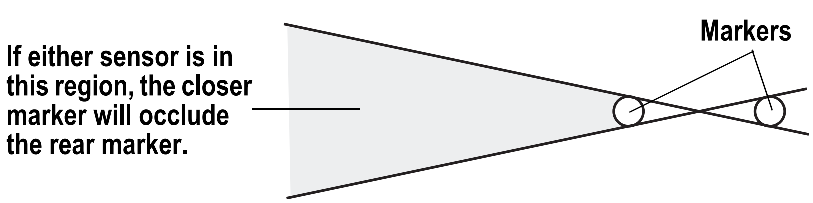
Figure 10-14 Obstruction Between Markers



The rest of this example explains how to determine the minimum size and location of such an obstruction.

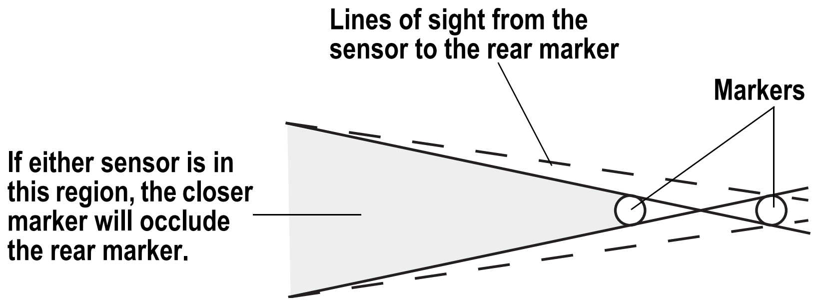
To determine the required size and location of the obstruction between a pair of markers, consider where the sensor can be positioned relative to the markers such that one marker partially occludes another. This is illustrated in Figure 10-15.

Figure 10-15 Sensor Location for Marker Occlusion



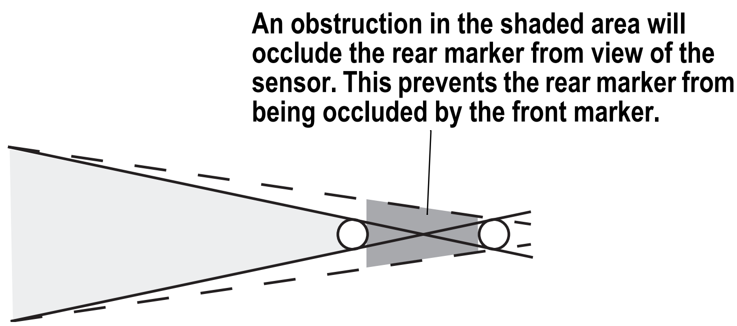
Now consider the lines of sight between the rear (partially occluded) marker and the sensor, when the sensor is in the zone highlighted in Figure 10-15. This is illustrated in Figure 10-16.

Figure 10-16 Lines of Sight from Sensor to Occluded Marker



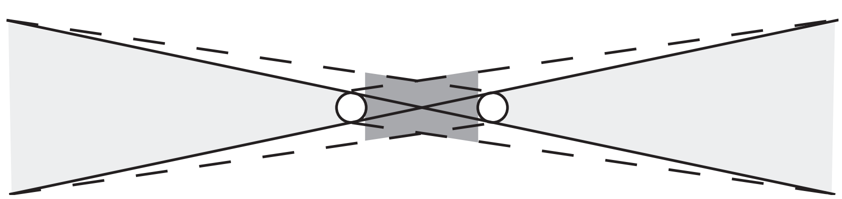
When those lines of sight are blocked, the front marker will never occlude the rear marker. We can place some obstruction between the two markers such that it blocks those lines of sight, as illustrated in Figure 10-17.

Figure 10-17 Prevent Marker Occlusion from One Side



The closer to the marker the rear obstruction is located, the smaller it needs to be. However, if the pair of markers may be viewed from the other side, the obstruction needs to be large enough to block the lines of sight from either side. The minimum size of the obstruction at various locations between the markers is illustrated in Figure 10-18.

Figure 10-18 Prevent Marker Occlusion from Any Side



The smallest obstruction is a disk placed exactly halfway between the two markers. The radius of the disk depends on the distance from the Position Sensor and the distance between the markers.

To stop the obstruction from partially occluding the tool (which can also lead to errors), set the maximum marker angle appropriately. An appropriate maximum marker angle (described on "Maximum Marker Angle" on page 49) stops the system from using the marker in the transformation before the marker can become partially occluded by the tool. This may mean setting the maximum marker angle parameter value to less than the default value.

11 Characterizing a Tool

This chapter describes how to characterize a tool:

11.1 Introduction

Characterization is the process of creating a tool definition file. A tool definition file is a file that describes a tool to the system. Without this information the system cannot accurately interpret the data it collects. Tools can be characterized using the NDI 6D Architect software.

> **After characterization, be sure to validate your tool to confirm it is operating as you expect and that it is returning correct transformations.**

11.2 NDI 6D Architect

NDI 6D Architect is a software application designed to characterize tools for use with NDI Polaris systems. The wizard interface allows you to create tool definition files in a step by step format. The software and user guide is available for download from the NDI Support Site. Refer to "Contact Information" on page vi.

11.3 Tool Definition Files

A tool definition file is created at the end of the characterization process.

- For passive and active wireless tools, the file must be loaded into the system before the system can track the tool.
- For active tools, the file is stored on a SROM device within the tool. The file is written to the SROM device at the end of the characterization process. You can also load a tool definition file for an active tool to the system to use instead of the file on the SROM device.

There are two types of characterization, that is, there are two methods for specifying the location of the markers on a tool:

Collection: The system detects all the markers on the tool to accurately determine the marker positions.

Engineering Data: You specify the tool's marker positions, using the engineering specifications that are used to manufacture the tool. The system does not need to detect the tool when the tool is being characterized using engineering data.

For active marker tools, mechanical tolerances and placement of markers prevent you from accurately knowing the location of the optical centre. Characterization using engineering data is not recommended.

For passive marker tools, the centre of the NDI Passive Sphere is always in the same position relative to the mounting post. If you wish to use engineering data to characterize a tool, the accuracy placement tolerance for the mechanical centre point of the marker must not exceed 0.05 mm.

> **For best accuracy for any classification of tool, use the collection method to characterize each tool individually.**

11.4 Characterization Best Practices

Consider the following best practices when you characterize tools. Poor characterization procedures may lead to a tool that produces inaccurate transformations, which may ultimately result in personal injury.

Before characterizing a tool:

- Make sure the lenses on the Position Sensor are clean and not damaged.
- Make sure the markers on the tool are not damaged.
- Confirm the accuracy of the Position Sensor, for example using the Accuracy Assessment Kit (AAK), before characterizing tools.
- Make sure the environment is representative of the environment in which the tool will be used.

While characterizing a tool:

- Orient the tool toward the Position Sensor to minimize off-angle markers.
- Make sure the tool and Position Sensor do not move during data collection.
- Take multiple data collections in different areas of the volume.

After characterizing a tool:

- Thoroughly test the tool and examine the tool RMS error. See "Validating & Testing Tools" on page 69.

11.5 Enhanced Tracking Algorithm Flags

Several different tracking algorithm flags can be set.

11.5.1 Three-Marker Lock-On

The three-marker lock-on option in the tool definition file enables the system to acquire (recognize) and track a tool as long as the system can detect at least three markers, regardless of the minimum number of markers parameter value.

How the system uses three-marker lock-on: When three-marker lock-on is enabled for a tool, the system will acquire the tool once it has determined three markers to be part of the tool and can use them to calculate a transformation. The system will continue tracking the tool as long as it can detect three markers and use them to calculate a transformation. The system will not report the transformations, however, unless the tool tracking parameters are all satisfied.

How three-marker lock-on improves performance: The three-marker lock-on option reduces acquisition time, which is useful when the system first starts tracking the tool or after the tool goes missing. The three-marker lock-on option also allows the system to continue tracking the tool as long as it can detect three markers, even if it cannot detect the minimum number of markers. This prevents the system from having to re-acquire the tool once it can detect the minimum number of markers again.

The improvement in performance, measured in frames, can be stated as:

[(minimum number of markers parameter value) - 3]

Setting three-marker lock-on: It is advantageous to enable the three-marker lock-on option, as long as the tool does not comprise three collinear markers (unless the tool is intended to be a 5DOF collinear tool). If the tool comprises three collinear markers, consider the case where some markers are occluded so that the system can detect only the three collinear markers. The system will not be able to consistently determine the orientation of the tool about the axis on which the collinear markers are positioned. Therefore, three-marker lock-on must not be set for a tool that comprises three collinear markers.

Example

Consider a four-marker tool with the three-marker lock-on option enabled. If the system can only detect three of the markers on the tool, it will continue to track that tool.

- If the minimum number of markers is set to 3, the system will report the transformations. In this case, it doesn't matter whether the three-marker lock-on option is enabled.
- If the minimum number of markers is set to 4, the system will continue to track the tool but will report that the tool is missing. Once the system has detected the fourth marker, it will calculate and report the transformations without having to re-acquire the tool.

11.5.2 Unique Geometry Tracking

The system uses the unique geometry tracking flag in the tool definition file to determine whether or not a tool should be tracked using the unique geometry algorithm.

Wireless Tools: Since the system recognizes wireless tools solely by marker geometry, all tools must follow the unique geometry constraints described in "Marker Geometry" on page 13, and the unique geometry tracking flag must be set in the tool definition file.

Active and Active Wired Tools: Set the unique geometry tracking flag for an active tool if the tool was designed to be a unique geometry tool. If the flag is not set, the system will not use the unique geometry algorithm to track the tool. For more information on unique geometry for active tools, see "Marker Geometry" on page 13.

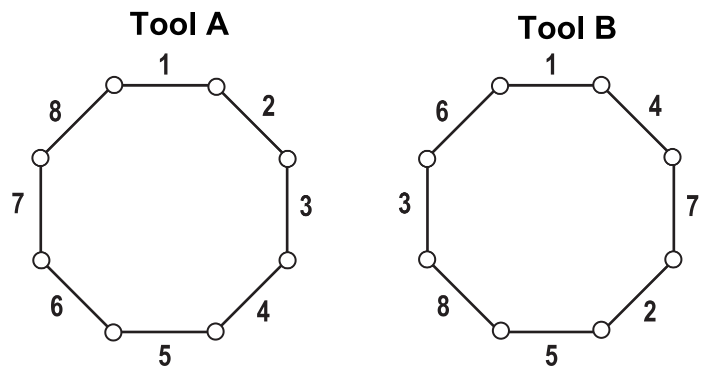
11.6 Marker Activation on Multi-Faced Tools

When a multi-faced active tool is being acquired (for the first time or after it goes missing), the system must activate each face of the tool in turn, starting with face 1, until it gets to a face that has enough markers in view to calculate a transformation. Certain marker activation sequences result in a faster average tool acquisition time.

Example - Marker Activation Sequence on an Eight-Marker Tool

Figure 11-1 shows two possible activating orders for an eight-sided tool. On both tools, the markers are located at the corners of each face; each marker is on two faces.

Figure 11-1 Multi-Faced Tool Activating Order



The Position Sensor will be able to detect at least two faces at a time. The system will, on average, be able to find tool B faster than it can find tool A. For example, if the Position Sensor is facing both tools from the side labelled “5”, it would detect tool A when it activates the fourth side, and tool B when it activates the second side.

11.7 Marker Normals and Face Normals

11.7.1 Marker Normals

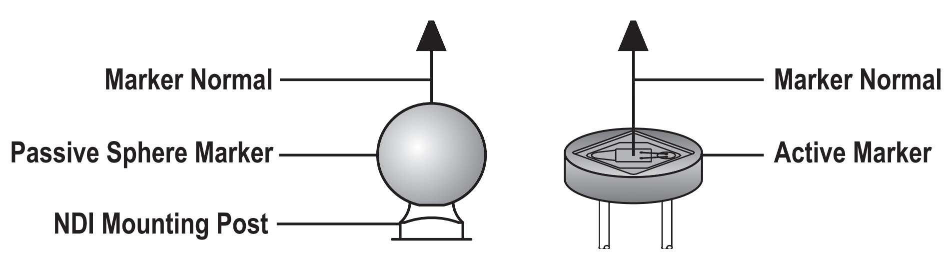
A marker normal is a vector of unit length (1 mm), and points in the same direction as the marker. Every marker on a tool has a marker normal.

How the system uses marker normals: The system calculates the angle between the marker normal and each sensor, to determine whether the maximum marker angle has been exceeded. If the maximum marker angle has been exceeded for some marker, the system will not use the data from that marker to determine the tool transformation.

How marker normals improve accuracy: Setting marker normals allows the system to make use of the maximum marker angle parameter. The maximum marker angle causes the system to stop using the marker data once the off-axis viewing angle has reached a certain level, reducing the possibility that the system will calculate inaccurate transformations.

Setting the marker normals: Marker normals are set in the local coordinate system of the tool. Thus, you must define the local coordinate system before you can set the marker normals. A marker normal should point in the same direction as the marker, as illustrated in Figure 11-2.

Figure 11-2 Marker Normals

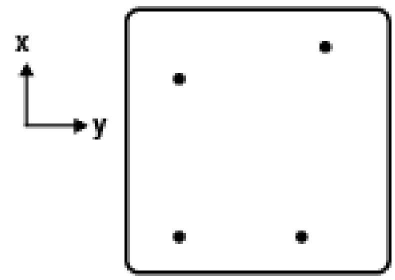


If marker normals are not set or are set incorrectly, the system cannot determine whether the maximum marker angle has been exceeded, which could result in inaccurate transformations. The marker normals can be set in NDI 6D Architect. 5DOF tools (where all the markers are collinear) must not be assigned marker normals.

Example - Setting Marker Normals for a Four-Marker Planar Tool

Consider the four-marker planar tool illustrated in Figure 11-3. The tool's local coordinate system is defined such that the markers lie in the *xy*-plane, and point in the *z* direction.

Figure 11-3 Setting Marker Normals



The marker normals for all four markers will be the same, since the markers all point in the same direction. Since the markers point in the *z* direction, the marker normals should be set to (*x*, *y*, *z*) = (0, 0, 1).

11.7.2 Face Normals

Face normals are vectors of unit length (1 mm), and are used on multi-faced tools to indicate which way each tool face is pointing. Every face on a multi-faced tool has a face normal.

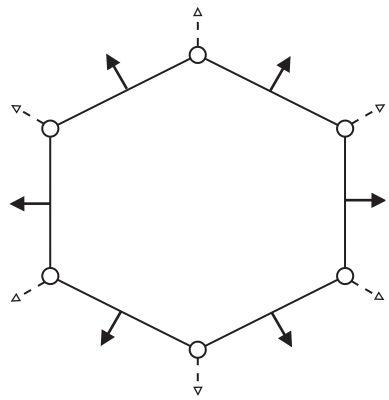
How the system uses face normals: The system uses face normals to determine which face to track on a multi-faced tool. The system will track the face whose face normal is pointing more directly towards the Position Sensor (i.e. the face with the smallest angle between the face normal and the sensors in the Position Sensor). If the minimum number of markers are not visible on the face most directly facing the Position Sensor, the system will attempt to track another face. The system has a hysteresis of 2° when determining whether to switch faces. The system will determine the angle between the sensors and each face of the tool. If the face with the smallest angle is 2° smaller than the current face's angle, the system will switch to the new face. This prevents the system from flickering back and forth between two faces if both faces are at the same approximate angle to the Position Sensor.

When the system is tracking a face, only the markers belonging to that face are used to calculate the tool transformation.

Setting the face normals: Face normals are set in the local coordinate system of the tool. Thus, you must define the local coordinate system before you can set the face normals.

A face normal does not necessarily point in the same direction as the markers which make up the face. For example, Figure 11-4 shows a tool with six faces, and all the tool's marker normals and face normals. The marker normals are represented by dotted lines, and the face normals are represented by solid lines.

Figure 11-4 Face and Marker Normals



If face normals are not set on a multi-faced tool or are set incorrectly, the system may not track the tool properly. The face normals can be set in NDI 6D Architect.

12 Validating & Testing Tools

This chapter describes methods for testing and validating tool designs:

12.1 Introduction

This chapter explains how to test a tool design in order to validate it:

- Tool Design Tests
- Electrical Tests for Active Tools

12.2 Tool Design Tests

12.2.1 Simulating Aspects of the Design

Once you have designed a tool, you can create a scale 3D model of the tool and the Position Sensor using a mechanical CAD package to simulate aspects of the design.

One aspect of the design that may be effectively simulated is the requirement that a minimum number of markers with a sufficient geometric spread be seen by the Position Sensor throughout the specified range of tool positions and orientations. This can be done as follows:

1. In the CAD software, place the tool at the desired position and orientation with respect to the Position Sensor.
2. Project a solid cone from each of the markers, pointing in the direction of the marker normal. The solid angle of the cone should be double the maximum marker angle.
3. If the cone corresponding to a particular marker envelops both sensors on the Position Sensor, then that marker will be visible at that position and orientation.

12.2.2 Testing the Final Design

After you have constructed a prototype for the tool, you can test the final design. The accuracy performance of the tool must be tested and documented through extensive bench testing. As a minimum, this analysis must consist of the following tests:

Test 1

1. Accurately move the tool to a measured set of representative positions and orientations. These measurements must be:
   - measured independently of the 3D localization system
   - traceable to an independent standard (e.g. National Institute of Standards and Testing or equivalent)

   These positions and orientations may be achieved with the use of precision translation and rotary stages and/or compound sine plates.
2. Compare the known positions and orientations of the tool with the positions and orientations measured by the Position Sensor.

Test 2

- For each of the positions and orientations in test 1, test the effects of fully or partially occluding all possible combinations of markers. The degraded accuracy performance is tested by again comparing the measured and known positions and orientations.

Test 3

- During testing, observe the RMS error that is returned with every transformation. The magnitude of the error is a function of the tool tracking parameter values (described in "Tool Tracking Parameters" on page 48). Undesirably high RMS errors indicate that the tool tracking parameters were not set appropriately.

There are many important protocols that might be selected to test each tool. In particular, the test must be able to discriminate between a tool that is performing marginally within and marginally outside specification. The variation in test results either repeated by the same tester or across different testers must be relatively small compared to the accuracy performance measurement itself.

12.3 Electrical Tests for Active Tools

12.3.1 Electrical Safety Test

In consultation with your safety agency, you should determine a suite of suitable safety tests, such as dielectric strength, for the tools and system.

12.3.2 Testing the Electrical Current

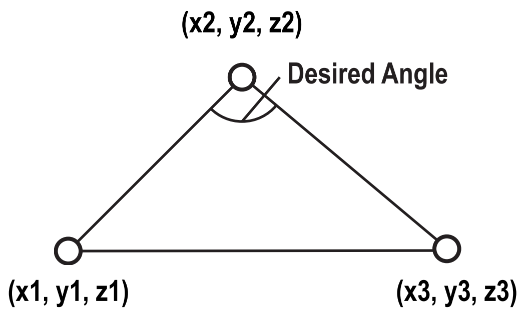
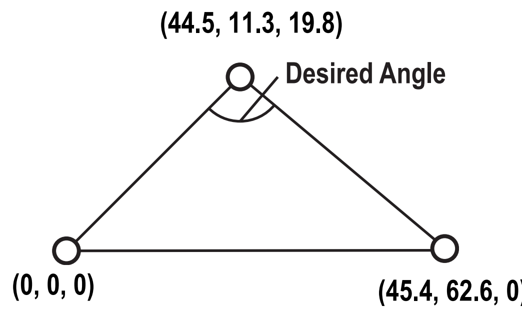
You can test the electrical current of a tool plugged into and SCU or strober by using the API command TCTST. This command should only be used to determine whether a marker is present, not to determine the magnitude of the current. You cannot test the electrical current of a visible LED, because the current is low and may be corrupted from electrical noise. For details on the TCTST command, see the application program interface guide that accompanied your Vega or Spectra system.

Appendix A: Determine the Segment Angle

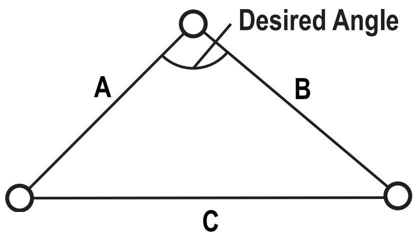
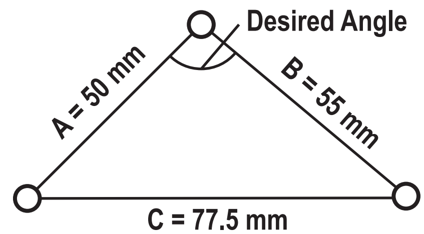
A.1 Introduction

This appendix describes two methods of determining the segment angle. The first method uses the 3D coordinates of the markers, and the second uses the segment lengths. The system uses segment angles to differentiate between tools, as described in “Groups” on page 22.

Figure A-1 Determining the Segment Angle Using 3D Coordinates

To Determine the Segment Angle:	Example:
1. The 3D marker coordinates are given by (x1, y1, z1), (x2, y2, z2), and (x3, y3, z3) for markers 1, 2 and 3, respectively.  	The 3D coordinates are as shown: 
2. Use the 3D coordinates of the three markers that define the angle to determine the dot product. Dot product = $(x1 - x2) \bullet (x3 - x2)$ $+ (y1 - y2) \bullet (y3 - y2)$ $+ (z1 - z2) \bullet (z3 - z2)$	Dot product = $(0 - 44.5) \bullet (45.4 - 44.5)$ $+ (0 - 11.3) \bullet (62.6 - 11.3)$ $+ (0 - 19.8) \bullet (0 - 0)$ Dot product $= -239.49$
3. Determine the maximum dot product magnitude. Maximum dot product magnitude = $\sqrt{(x1 - x2)^2 + (y1 - y2)^2 + (z1 - z2)^2}$ $\bullet \sqrt{(x3 - x2)^2 + (y3 - y2)^2 + (z3 - z2)^2}$	Maximum dot product magnitude = $\sqrt{(0 - 44.5)^2 + (0 - 11.3)^2 + (0 - 19.8)^2}$ $\bullet \sqrt{(45.4 - 44.5)^2 + (62.6 - 11.3)^2 + (0 - 19.8)^2}$ Maximum dot product magnitude $= 2737.94$
4. Use the dot product and the maximum dot product magnitude to determine the normalized dot product. Normalized Dot Product = $\dfrac{\text{Dot product}}{\text{Maximum dot product magnitude}}$	Normalized dot product $= \dfrac{-239.49}{2737.94}$ Normalized dot product $= -0.087$
5. Use the normalized dot product to calculate the segment angle. Segment angle $= \text{acos}(\text{normalized dot product})$	Segment angle $= \text{acos}(-0.087)$ Segment angle $= 95.02°$

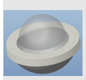
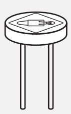
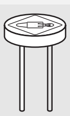
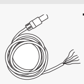
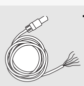
A.2 Determining the Segment Angle

<table>
<tr><th>To Determine the Segment Angle:</th><th>Example:</th></tr>
<tr><td>1. The segment angles are given by A, B and C. Segments A and B meet at the desired segment angle.

</td><td>The segment lengths are as shown:

</td></tr>
<tr><td>2. Use the law of cosines to determine the segment angle.
$$\text{Segment angle} = \operatorname{acos}\left(\frac{A^2 + B^2 - C^2}{2 \bullet A \bullet B}\right)$$</td><td>$$\text{Segment angle} = \operatorname{acos}\left(\frac{50^2 + 55^2 - 77.5^2}{2 \bullet 50 \bullet 55}\right)$$
$$\text{Segment angle} = 95.02°$$</td></tr>
</table>

Appendix B: NDI-Supplied Parts

This appendix lists parts that are available for purchase from NDI.

Table 12-1 NDI-Supplied Tool Parts

Tool Part	Part Number	Details
 NDI Passive Sphere	1201115	Single-use sterile NDI Passive Spheres are available from Scanlan International (www.scanlaninternational.com).
 Standard mounting post	1201101	See page 30.
 Radix Lens	8800885	See page 2.
 Active marker	3000199	See page 27.
 Photodiode in ceramic package	10000646	See page 33.
 Tool cable	2600487	See page 42.
 Tool cable assembly	120096	See page 42.

Abbreviations & Acronyms

This chapter provides a list of the abbreviations and acronyms used in this guide.

Abbreviation	Definition
5DOF	5 Degrees of Freedom
6DOF	6 Degrees of Freedom
IR	Infrared light
IRED	Infrared light emitting diode
LED	Light emitting diode
NDI	Northern Digital Inc.