Metria Innovation, Inc.

Moiré Phase Tracking™ Technology
Metria Innovation, Inc.

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1 Introduction

Moiré Phase Tracking™, or MPT, is a single-camera 3D motion tracking technology that incorporates a specially designed passive optical marker. Figure 1 illustrates the flow of information in a Series2 MPT System, starting with the motion of MPT markers and culminating in recorded measurements. Though not shown in the figure, the Series2 System can also stream measurements live over the network, using either gigabit ethernet or WiFi.

Figure 1: Basic elements of the Metria Motion Capture System.

Series2 System Features

- Unique use of moiré patterns, enabling full 3D motion capture with a single camera
- Translation and rotation recorded for each marker in every image
- Because of moiré patterns, rotations are accurate to ±0.05° RMS
- Automatic identification of up to 256 markers in each image
- Synchronized capture of 16 channels of analog data
- Data output in ASCII and C3D file formats
2 Quick start guide

Figure 2: Series2 System Components (left to right): MPT Marker, Camera Lighting Unit (CLU), Measurement Controller (MC)

2.1 Equipment Setup

The following is an abbreviated list of equipment setup steps. See Section 3 for detailed steps with illustrations.

1. Mount the Camera Lighting Unit (CLU) on a tripod or other fixed mount.

2. Connect the CLU to the Measurement Controller (MC) using the appropriate data and power cables. The CLU should have no empty sockets.

3. Plug the MC into the wall, and turn it on by pressing the power button on the front of the unit.

4. Place MPT markers in the CLU field of view.

5. Boot the user-supplied computer which will run MoCapClient (Section 2.2).

Figure 3: Rear view of CameraLink (left) and USB (right) Series2 Systems
2.2 Software Setup

The Series2 System is operated using MoCapClient, a User Interface program which runs on a Windows, Linux, or Macintosh computer supplied by the user. To set up MoCapClient:

1. Connect your computer to the Measurement Controller (MC) using one of the following methods:
   
   (a) Connect an ethernet cable from your computer to the port labeled **DHCP** on the back of the MC.
   
   (b) Connect to the MC via WiFi:
       
       • **SSID**: **MetriaDevice-Series2SN** where *N* is your Series2 System serial number.
       
       • **Password**: **MetriaDeviceWifi**

2. Once your computer is connected to the MC, open the program file **MoCapClient.jar** by double-clicking its icon. MoCapClient requires a recent version of Java.

3. MoCapClient should automatically find your Series2 System and show a preview of what the camera sees. MPT Markers will be identified and circled, as in Figure 4.

4. Press the **Add Acq** button in the Protocol Panel (Section 4.2), and the **Acquisition Settings** dialog will appear. Fill in an **Acquisition Name** and press the **Commit** button; this will return you to the main window.

5. Press the **Acquire Next** button in the lower right of the main window. When prompted, press the **Fire** button to collect your first acquisition (Section 4.3).

6. Measurement results for any markers in the camera field of view during acquisition will be put into the **Results Root** directory (Section 4.6.1, Panel 5 in Figure 15).
3 Detailed Equipment Setup

3.1 The Camera-Lighting Unit

The components of the Camera-Lighting Unit (CLU) are shown and labelled in Figure 5.

![Figure 5: Camera-Lighting Unit Components](image)

Figure 5: Camera-Lighting Unit Components

Figure 6 illustrates the procedure for mounting the CLU to a tripod. First, remove the camera plate from your tripod and screw it into the 1/4-20 threaded hole on the bottom of the CLU base. Next, reattach the camera plate to the tripod, making sure it is fastened securely.

![Figure 6: Mounting the CLU](image)
3.2 Camera-Lighting Unit Cables

Each Camera-Lighting Unit (CLU) utilizes three kinds of cables: A power cable which connects to the power jack on the CLU base (Figure 5), a trigger cable which connects the camera to the CLU base, and one or two data cables.

**Warning:** All cables must be hand tightened only. Use of tools may damage the system.

It is easiest to install the trigger cable first, as shown in the left panel of Figure 7. Note that the trigger cable connector must be oriented properly to fit in its socket – Do not force it into place!

The USB version of the Series2 System has a single data cable that fits only one way. The CameraLink version has two cables labelled *Base* and *Full* which are easily confused. Be sure to align these cables with the letters *B* and *F* on the camera body, otherwise the system will not work.

![Figure 7: CameraLink (left two panels) and USB (right panel) CLUs with cables](image)

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3.3 Measurement Controller Cables

3.3.1 CLU Related

The CLU power cable connects to a jack on the Measurement Controller (MC) labelled “CAM PWR” which looks just like the one on the CLU base (Figure 5).

The data cable for USB systems may plug into any USB port on the back of the MC. If this connector is not fully inserted, the system will only function at USB 2 speeds, and the camera will not work.

The two data ports for CameraLink systems are labelled *Base* and *Full*. Match these to the labels on the CameraLink cables, otherwise the system will not work.

**Warning:** *All cables must be hand tightened only. Use of tools may damage the system.*

![Figure 8: Fully wired CameraLink (left) and USB (right) systems](image)

Of course, you will also want to plug the MC into the wall – its AC power cable is shown in Figure 8.
3.3.2 Analog Input

Optionally, one can use analog input of the Series2 System by connecting the ribbon cable and analog breakout box to the Measurement Controller (MC), as shown in Figure 9.

![Figure 9: Connecting the analog breakout box to the MC](image)

Once connected, it is possible to bring in analog signals to any of the channels on the breakout box. It is important to install terminators on any channels not in use, in order to reduce noise and crosstalk between the channels. This setup is shown in Figure 10.

![Figure 10: Analog inputs connected to breakout box with terminators on unused channels](image)
The Series2 System Analog Input may be used to record data from items including but not limited to force plates, EMG sensors, and any other general electrical signals to the analog input. It is based off a PCI-DAS6013 by Measurement Computing (http://www.mccdaq.com/) (See Appendix 30).
3.4 Networking

There are several networking topologies available depending on user desire and available equipment. For all topologies, the main measurement controller (labelled Single/Master below) will have an IP address of 192.168.2.1, and any machine connected to it will receive an IP address of 192.168.2.N via DHCP.

3.4.1 Wireless

In normal operation the Measurement Controller (MC) acts as a wireless (WiFi) access point. Any computer with a wireless interface can connect to the measurement controller just like any other wireless network.

- SSID: `MetriaDevice-Series2SN` where $N$ is your Series2 System serial number.
- Password: `MetriaDeviceWifi`

The MC will seek out the best connection possible based on the surrounding wireless environment. It is capable of 802.11n speeds up to 150MB/s, but performance can drop to 802.11g speeds of 54MB/s if the environment is noisy or the user supplied computer has an older wireless adapter. Data throughput of 54MB/s will be enough to provide stutter-free performance.

3.4.2 Single system wired connection

It is possible to connect to the Measurement Controller (MC) via ethernet cable, eliminating the problems that can arise from a noisy WiFi environment. To do this, run a network cable from the user computer to the ethernet port labeled `DHCP` on the MC. The connection should be established automatically. If it isn’t, make sure the user computer network interface gets its IP address through the DHCP protocol.

![Figure 11: Wired ethernet control with one MC (Single)](image-url)
3.4.3 Multiple system wired connection

It is possible to connect multiple Measurement Controllers (MCs) together. In this configuration, measurements are synchronized across all systems. The amount of data involved, however, requires that the systems be connected via ethernet.

As shown in Figure 12, the user computer and all MCs connect to each other through an ethernet switch. One (and only one) MC must connect to the switch from its DHCP ethernet port. This machine is called the Master. It gives ethernet addresses to all of the other MCs, which are called Followers. They connect to the switch from their LAN ethernet ports.

Once a follower MC has connected to the master MC, its WiFi will stop, and it will synchronize with the master MC. This process can take up to 30 seconds. Please wait at least this long before collecting data with the system.

![Wiring diagram of a multi-controller system]

Figure 12: Wiring diagram of a multi-controller system
4 MoCapClient: The Series2 User Interface

The user interacts with the Series2 system through MoCapClient, a platform independent user interface program. MoCapClient will run on any operating system that supports a recent version of Java. Its main window and settings window are shown in Figures 13 and 14.

![MoCapClient Main Window](image)

Figure 13: MoCapClient Main Window upon launch.
Figure 14: MoCapClient Settings Window
4.1 Terminology

4.1.1 Main Window Panels

The MoCapClient main window is divided into 7 sections or panels. These are named in Table 1 and highlighted in Figure 15. Each panel has a different role to play in operating the Series2 System. They are labelled here, at the outset, for convenient reference later on.

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Table 1: Panel Labels

![Figure 15: MoCapClient Main Panels](image-url)
4.1.2 Acquisition

An acquisition is the basic unit of data collection in the Series2 System. When one runs or fires an acquisition, the system collects data for a set number of images or frames from the camera and saves the resulting measurements to a data file (or data files, when analog input is enabled). For example, if the camera is running at 90 frames per second, an acquisition of 900 images will collect data for 10 seconds.

Each acquisition has a unique name and an iteration counter, both of which appear in the name of the data file(s) created by the acquisition. The iteration counter starts at 1 and increases every time the acquisition is fired. If an acquisition is named longAcq, its output data files will have names like longAcq1.hts, longAcq2.hts, longAcq3.hts, and so on. If analog input is enabled, longAcq1.ana, longAcq2.ana, . . . will also be available. If C3D file output is properly configured, longAcq1.c3d, longAcq2.c3d, . . . will be available as well.

4.1.3 Protocol

A protocol is a list of acquisitions that can be saved and reloaded in MoCapClient. The names of the acquisitions, their order in the protocol list, and the number of images set for each acquisition are all stored in the protocol. This allows users to conveniently reuse a particular data collection setup.
4.2 Adding and Editing Acquisitions

To add an acquisition, hit the *Add Acq* button in the protocol panel (Figure 13 Panel 6). This will open the Acquisition Settings Window (Figure 16), where one can set the Acquisition Name and Number of Images. Number of Images has a minimum value of 10 and a maximum value limited by the amount of RAM in the Measurement Controller.

Optionally, a Detailed Description may be added to an acquisition. This description is viewable only when adding or editing an acquisition; it is useful if the Acquisition Name is unclear.

If Confirm to Fire is checked, the Fire Confirmation Dialog (Section 4.3.1) will appear and require another button to be pressed before data is actually collected. Acquisition Repetitions sets the number of times an acquisition is fired every time firing is initiated. It is a form of auto repeat covered in Section 4.3.2.

![Acquisition Settings Window](image)

To the left (Revised: Aug 12, 2012)

Figure 16: Protocol Panel and Acquisition Settings Window

Added acquisitions appear in the Acquisitions Panel (Figure 15 panel 7). Figure 17 shows a compressed Acquisitions panel with three acquisitions named *long*, *medium*, and *short*. To the left

![Acquisitions Panel](image)

Figure 17: Acquisitions panel with three configured acquisitions
of each acquisition is a circle called a *Radio Button*. The radio button for the *long* acquisition is filled in, meaning this acquisition is *selected*. To change the settings of the selected acquisition, click the *Edit Acq* button in the protocol panel (Figure 16). This opens the Acquisition Settings window with all the settings of the selected acquisition. Any changes made can be saved by hitting the *Commit* button.

Any acquisition can be selected by clicking on the radio button to the left of the acquisition.

### 4.3 Firing Acquisitions

The Acquisitions Panel (Figure 18) provides two mechanisms for firing acquisitions. One way is to simply click the button bearing the name of the acquisition. This will fire it. The other way is to click the *Acquire Next* button in the bottom right of the Acquisitions Panel. This will fire whatever acquisition is selected. After the acquisition has completed, the next acquisition will be selected. Hitting the *Up* button causes the previous acquisition to be selected.

In Figure 18, the acquisition named *long* is selected (the radio button to its left is filled in with a black dot). After firing with Acquire Next, the acquisition named *medium* will be selected. If the acquisition named *short* is fired with Acquire Next, *long* will be selected after *short* has finished acquiring.

![Acquisitions Panel](image)

Figure 18: Acquisitions panel before (left) and after (right) *Acquire Next*

To the right of each acquisition is its iteration counter. This counter begins at 1 and increases every time an acquisition is fired. This number appears in the name of the data file(s) created by an acquisition, allowing acquisitions to be fired multiple times without overwriting data. Hitting the *Acquisition Iteration Reset* button will reset all acquisition iteration counters to 1.

Whenever an acquisition is fired, a window pops up to notify the user that data acquisition is in progress. That window for the acquisition named *long* is shown in Figure 19.
4.3.1 Fire Confirmation

If Confirm to Fire is selected in an acquisition’s settings (Section 4.2), the dialog of Figure 20 will appear whenever the acquisition is fired. Data collection will only start after the Fire button in this dialog is pressed. Hitting the Cancel will abort data collection. This is very handy when the system is operated using a presenter tool, as it allows the user to be sure the correct acquisition has been selected before collecting data.

4.3.2 Repeated Acquisitions

If Acquisition Repetitions is set to a value greater than 1 in the Acquisition Settings Window (Figure 21), the acquisition will be fired multiple times whenever firing is initiated by any of the methods in this section. If Confirm to Fire is on and Acquisition Repetitions is set to 10, the acquisition will be fired 10 times consecutively after the Fire button of the Fire Confirmation Dialog is pressed once.
4.4 Arranging Acquisitions

The *Move Up* and *Move Down* buttons in the Protocol Panel (Figure 22) move the currently selected acquisition up or down in the list of acquisitions in the Acquisitions Panel. The acquisition named *long* is shown as selected in Figure 22. Since it is at the top of the acquisitions list, the *Move Up* button will not affect it. The *Move Down* button will cause the *long* acquisition to change places with the *medium* acquisition.

4.5 Creating, Loading, and Saving Protocols

Since a protocol is defined by the list of acquisitions, a protocol is created by adding, editing, and arranging acquisitions (Sections 4.2 and 4.4). A protocol also has a name, which is set using the *Name:* field in the Protocol Panel (Figure 23).

A protocol may be saved to a file using the *Save* button in the Protocol Panel. Once saved, a protocol may be loaded later using the *Open* button in the Protocol Panel. The list of acquisitions
in the Acquisitions Panel will be the same as when the protocol was saved, except all Acquisition Iteration counters will be set to 1.

The New button in the Protocol Panel deletes the current protocol and sets the protocol name to New. Be sure to save the existing protocol before hitting the New button.

![Protocol Panel Image]

**Figure 23: Protocol Panel**

### 4.6 Organizing Measurement Data Files

#### 4.6.1 Results Root

Measurement data files are saved under the Results Root directory, which is configured using the Results Root button in the Sessions Panel (Figure 24).

![Sessions Panel Image]

**Figure 24: Sessions Panel**

#### 4.6.2 Results Path

The filename and directory structure used to save the measurement data files may be configured using the Results Path Config section (Figure 25) of the Settings Window (Figure 14). Hit the gear shaped settings button on the Banner Panel (Figure 4.1.1 Panel 1) to open the Settings Window.
Figure 25: Settings Button and Results Path Configuration

The Results Path (or simply path) is an expanded filename of a measurement data file, including the directories leading to it from the Results Root directory. The Results Path Config section has a list of fields that can be entered into the path where measurement data files are saved. These include Plan Name, Acq Name, and Acq Iteration (See Section 4.6.3 for Dynamic Labels). To the left of each field are three radio buttons labelled \, _, and x.

- The \ setting causes a field to begin a new directory in the path.
- The _ setting includes a field as part of the path, but does not use it to begin a new directory. An underscore is added before the field when needed.
- The x setting removes the field from the path.

Results Path Example shows what the Results Path will look like in practice. Changes to the Results Path will be lost unless the Save Configuration button is pressed before exiting the Settings Window.

4.6.3 Dynamic Fields

Dynamic Fields are configurable Results Path fields that allow general information about a data collection session to be included in the Results Path. The labels of Dynamic Fields (Dynamic Labels) are entered in the Results Path Config section of the Settings window; the Dynamic Fields themselves are displayed in the Session Panel of the Main Window.

Figure 26 includes both locations involved with Dynamic Fields. It shows Dynamic Labels 1 and 2 set to Tester and Subject in Settings. The Tester and Subject fields receive the values Jane and S19 in the Main Window. The Results Path is configured to create a directory that stores acquisitions for each Tester, while the Subject field is connected to the acquisition name and iteration counter. A filename such as JaneS19_standing_1.hts will result.
4.7 Camera Settings

Figure 27 shows the Camera Panel. It has several features:

**System**  The name of the Measurement Controller (MC) to which MoCapClient is connected. This dropdown menu is essential to setups with multiple MCs.

**Framerate**  The camera framerate of the connected system, in units of frames per second. Its minimum value is 1 frame per second, and its maximum value is set by the camera hardware.

**Exposure**  Technically, the number of microseconds that the camera imager is exposed for every frame. Setting this number higher results in a brighter image.

**Analog Ratio**  The number of analog samples per channel that are saved for every frame of camera data. If the camera runs at 90 frames per second, and Analog Ratio is set to 10, each analog channel will run at 900 samples per second.

**Ring Light**  A button which may be used to turn the CLU ring light (Figure 5) On or Off.
4.8 Preview Settings

The Preview Panel (Figure 15 Panel 2) is designed to display what the camera is seeing in a helpful manner. It has many capabilities and settings, which may be adjusted via the Dash Panel (Figure 15 Panel 3) and which are described below.

![Preview Window Markers & Marker Info](image)

**Figure 28: Preview Window Markers & Marker Info**

4.8.1 Image, Markers, Diagnostics

The Dash Panel has four checkboxes for image- and marker-related features available in the Preview Panel:

- **Image** Displays the grayscale image seen by the camera.
- **Marker Info** Displays full marker ID, marker brightness, and marker focus index.
- **Markers** Places colored circles over markers identified by the system. Marker ID is displayed inside each circle, and the colors match those of the relevant Marker Info line.
Diagnostics Displays system diagnostic information.

The above four features may be turned on or off in any combination. Figure 28 shows Markers and Marker Info together, Figure 29 shows Image and Diagnostics together. Turning off all four options results in a black Preview Panel.

![Figure 29: Preview Window Image & Diagnostics](image)

4.8.2 Analog

The Preview Panel is also able to display data from Analog Input. Figure 30 shows Channels 1 and 2 together on the same screen. Each channel receives its own color, and 0V coincides with the centerline of the voltage readout text.

The Analog Gain setting in the Dash Panel comes in handy for faint signals. It can be set anywhere from 1 to 100 and is simply a multiplier applied to the Analog Input data before display.
Figure 30: Analog Channels 1 & 2 displayed
4.9 Tracking Config

While any readable markers are in the field of view of the camera, the Series2 system will try track their position immediately and send the measurement as a UDP packet. The destination port and address of these packets can be set using the Tracking Config panel shown (Figure 31). The structure of the UDP is defined in Appendix 6.6.

The number of markers that a system can track at any given time is based on a number of factors, including but not limited to, scene brightness, current processing of acquisitions, system temperature and number of markers in the scene. Due to these uncertainties the system will only attempt to send UDP measurement packets using a “best effort” algorithm. An unloaded system can reasonably be expected to track markers at about 500 measurements per second. To say this another way, a user could reasonably expect to track 5 markers in realtime at a framerate of 100fps.

4.10 Room Coordinates

By default, all Series2 marker measurements are given in camera coordinates (See Section 6.7.1). In some applications, measurement data may be easier to visualize or interpret if represented in another coordinate system; commonly, a coordinate system aligned with the floor of a room or another flat surface is chosen. The Room Coordinates section of the settings window (Figure 32) allows such a coordinate system to be established by recording three points using the pointing tool (Section 6.5). The three points are:

1. The origin of room coordinates.

2. A point on the X axis of the room coordinate frame.

3. A point on the XY plane of the room coordinate frame not colinear with the X axis.
To set each of these points, hold the tip of the pointing tool at the point’s location and hit the appropriate button in the Room Coordinates section of the Settings Window (Figure 32). If something goes wrong with a point measurement, it may be cleared and re-measured. Once all three points have been recorded, the room coordinates transform, rcT, will be calculated, and all subsequent marker measurements will be given in room coordinates. For more information, see Section 6.7.3.

4.11 Force Plate Registration

Force plate registration causes Series2 marker measurements to be recorded in the coordinate frame of an attached force plate. To register a force plate, first record the tare information by hitting the Acquire unloaded forceplate button in the Registration section of the Settings Window. Next, push the tip of the pointing tool (Section 6.5) firmly into the force plate at a point away from the force plate center. Have another operator hit the Acquire forceplate point A button while the pointing tool is held in this condition. Repeat at two other points (B and C), chosen such that the three points are some distance from the force plate center and are not colinear.

Once the unloaded force plate and all three points have been acquired, hit the Perform forceplate registration button. Finally, hit Propagate registration to cameras. Subsequent marker measurements should be given in the force plate coordinate frame (for which, see Section 6.7.4).
4.11.1 Force Plate Registration with Multiple Cameras

For systems with multiple cameras, an additional task must be performed between hitting *Perform forceplate registration* and hitting *Propagate registration to cameras*. That task is *Camera Registration*, which determines the relative 6 DoF pose between all cameras in a multi-camera Series2 setup.

Camera registration is performed by taking a special acquisition that is initiated by the *Acquire for camera registration* button in the Registration section of the Settings Window. While the acquisition is running, a set of two or more markers which are rigidly affixed to each other must be seen by all pairs of cameras in the multi-camera setup. The rigidity criterion helps the camera registration algorithm distinguish the markers used for camera registration from any background markers. Moving the registration markers during the acquisition also helps to the same end.

Once the registration acquisition has completed, press the *Perform camera registration* button. A window will pop up with statistics relating to the registration, and possibly a warning if something went wrong. If everything looks ok, hitting *Propagate registration to cameras* will complete the force plate registration procedure.

**Registration Marker Sets** For cameras which have overlapping fields of view, a set of registration markers can be created by affixing at least two MPT markers to a rigid plate, as shown in Figure 34.

![Figure 34: Camera Registration Plate](image)

For cameras with non-overlapping fields of view, such as a pair of cameras facing each other, a
more ingenious solution is required. One option is a solid cube of material with markers affixed to the sides, as shown in Figure 35. Spinning this cube along its top-bottom axis allows the camera registration algorithm to solve for the relative poses of the registration markers. As long as any two of the registration markers can be seen by both cameras at the same time, camera registration will succeed.

Figure 35: Camera Registration Cube

**Warning** If a cube like the one in Figure 35 is used for camera registration, care must be taken when placing markers on it. The principal starburst lobe (shown by a yellow line) of each marker
must align with the top or bottom of the cube. This is to prevent a rotation of 90° about the X axis of any markers in the registration set, which would cause the Euler angles used in the camera registration algorithm to enter an undesirable state known as gimbal lock.
## 5 Indices

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Appendix

6.1 Homogeneous transform file format

The homogeneous transform file format is illustrated in Table 2. The initial lines are comments, providing information about the acquisition. Each subsequent line corresponds to one captured image and contains

1. An initial string
2. The frame time, in units of seconds
3. \( N_t \) repetitions of 14 fields, where \( N_t \) is the number of MPT markers identified in the acquired images. The fields are
   
   (a) The MPT marker ID number
   
   (b) The status of measurement for this MPT marker in this image, where 1 := valid data, and 0 := no valid data
   
   (c) Twelve elements of the homogeneous transform matrix, expressing the pose of the MPT marker in the coordinate frame of the motion tracking camera

For example, for the first row of data in table 2, the homogeneous transform is given as

\[
\begin{bmatrix}
-0.840866 & 0.392027 & 0.373174 & 0.007651 \\
0.530461 & 0.733847 & 0.424358 & 0.038187 \\
-0.107493 & 0.554782 & -0.825022 & 1.552948 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

The last row of every homogeneous transform, \( \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \), is omitted from the homogeneous transforms file. The homogeneous transform translation part (the last column in Equation 1) is given in meters.
Table 2: Sample of the homogeneous transform file format.
6.1.1 Re-Orthonormalization

The upper-left $3 \times 3$ submatrix of $\mathcal{T}$, called $\mathcal{R}$, is a Rotation matrix. Starting from $\mathcal{T}$ in Eqn 1,

$$
\mathcal{R} = \begin{pmatrix}
-0.840866 & 0.392027 & 0.373174 \\
0.530461 & 0.733847 & 0.424358 \\
-0.107493 & 0.554782 & -0.825022
\end{pmatrix}.
$$

(2)

The columns of rotation matrices must be mutually orthogonal and normalized to unit length, that is, rotation matrices are orthonormal matrices. Because the elements of $\mathcal{R}$ are given to only 6 significant digits in the data file, $\mathcal{R}$ will no longer appear orthonormal when its elements are converted to 64-bit floating point. Orthonormality is restored by the following procedure:

$$
[U, S, V] = \text{svd}(\mathcal{R})
$$

(3a)

$$
\mathcal{R} = U \cdot S \cdot V^T
$$

(3b)

$$
\mathcal{R}_\perp = U \cdot I \cdot V^T = U \cdot V^T.
$$

(3c)

Eqn 3b is inserted only to clarify the matrix variables used with the Singular Value Decomposition (SVD) in Eqn 3a. The needed step is Eqn 3c, which produces $\mathcal{R}_\perp$: the nearest matrix to $\mathcal{R}$ which is orthonormal to machine precision.

**WARNING**  The procedure of Eqn 3 must be applied to the rotation matrix part of every homogeneous transform which is converted to floating point numbers from a data file. If this procedure is not performed, data corruption will occur. Not only are numerical errors introduced by having non-orthogonal columns in $\mathcal{R}$; trigonometric routines operating on a non-orthonormal $\mathcal{R}$ may even return imaginary numbers.
### 6.2 External input file format

An example of the external input file format is illustrated in Table 3. The first line contains a comment with the name of the system on which data was collected. The first column of each subsequent line contains a measurement timestamp in units of seconds. The remaining columns hold the measurement data, in units of Volts, for the configured external input channels. In the case of Table 3, the system was configured to save data from the first six external input channels.

```
% System: Series2S11
00083742.697129420, 2.388800, 2.418708, 2.443732, 2.468757, 2.493782, 2.518807
00083742.701129780, 2.358892, 2.383917, 2.408637, 2.438849, 2.463874, 2.488899
00083742.705130141, 2.328679, 2.353704, 2.378729, 2.403754, 2.428779, 2.458686
00083742.709130502, 2.293889, 2.318914, 2.348821, 2.373846, 2.398871, 2.423896
00083742.713130863, 2.263676, 2.288701, 2.313725, 2.338750, 2.368658, 2.393683
00083742.717131224, 2.228885, 2.258793, 2.283818, 2.308843, 2.333867, 2.358892
00083742.721131585, 2.198672, 2.223697, 2.248722, 2.278935, 2.303655, 2.328679
00083742.725131946, 2.168765, 2.193790, 2.218814, 2.243839, 2.268264, 2.298772
```

Table 3: Sample of the external analog input file format.

### 6.3 Analog sampling specification

PCI-DAS6013 by Measurement Computing (http://www.mccdaq.com/)

- Number of Analog Channels: 16
- Input Range: -10V to 10V
- Data Resolution: 16 bits per reading per channel
- Sample Rate: 200,000 samples per second across all 16 channels (12,500 samples per second each channel)
- Number of Digital I/O Channels: 8
- User selectable number of channels: 0 to 16 inclusive.
- User selected sample rate: Up to 200k samples/second (one channel) or 12k samples/second (sixteen channels).
6.4 Marker Barcodes

The Series2 System determines the ID number of an MPT marker by reading its barcode, which is a binary form of the ID number encoded in barcode triangles on the face of the marker; these are highlighted in Figure 36. Bright barcode triangles represent the 1 or ON state of the binary code, while dark barcode triangles represent the 0 or OFF state. The binary values of the barcode triangles in the ON state are added to produce the marker ID number. The binary values are shown in Figure 36, and they increase in clockwise order around the marker, starting at the yellow line connecting the principal lobe of the central starburst to the circular landmark with which it aligns. The principal lobe is the only starburst lobe that points directly at a circular landmark.

A Marker ID may take on any value in the inclusive range of 1 to 255. The marker in Figure 36 has a ID number 39 (1+2+4+32).

![Figure 36: Barcode triangles and their binary values](image)

6.4.1 Marker Series

Each MPT marker has a unique factory calibration and therefore must be uniquely identified to achieve reliable measurements. Since there are many more than 256 markers in production, each marker is given a 4 digit marker series number in addition to a marker ID number. A marker with series number 1002 and ID number 043 is referred to by its unique ID 1002:043.

The Series2 system can only read the marker ID number during data capture, as the marker series number is not stored in the barcode. Consequently, markers with the same ID number but different series numbers cannot be used at the same time. Customers with fewer than 256 markers can ignore this detail. Special instructions will be given to customers with more than 256 Markers.
6.5 Pointing Tool

A pointing tool is shown in Figure 37. It consists of an MPT marker firmly attached to a machined delrin rod that tapers to a point at the tip. Each pointing tool goes through a factory calibration procedure that determines the location of the tip in the coordinate frame of the MPT marker. That means the 3D location of the pointing tool tip is known whenever the marker is measured. In this manual alone, the pointing tool is used for setting up room coordinates (Section 4.10) and registering force plates (Section 4.11). It comes in handy any time one needs to locate a point in 3D space.

![Figure 37: Pointing Tool](image)

When a pointing tool is present during an acquisition, its tip coordinates will appear in the header of the resulting measurement data file (Section 6.1). The header line will look like the following:

```
```

The Series and ID tokens precede the series number and marker ID of the pointing tool marker, while the 3 element vector following the tPu token gives the pointing tool tip location in millimeters. It is arranged in the order [ X Y Z ]. Be careful when using these tip coordinates with the homogeneous transforms in the measurement data file, as the homogeneous transform translation part is given in meters (Section 6.1).
6.6 Tracking Packet Structure

The Series2 system outputs its realtime tracking results in UDP packets with the structure shown in Table 4. Section 4.9 shows how to set the destination for tracking packets using the MoCapClient user interface.

```
typedef struct UDPPacketV100_s {
    int version;
    char hostname[64];
    int frameNumber;
    unsigned int frameTime_sec, frameTime_nsec;
    unsigned int irqSequenceNum;
    unsigned int irqTime_sec, irqTime_nsec;
    struct {
        int markerSeriesNumber;
        float markerWidth;
        float markerThickness;
        float x, y, z;
        float qr, qx, qy, qz;
        unsigned int flags;
    } aMarkers[256];
    double aVoltages[16];
} UDPPacketV100_t
```

Table 4: UDP Tracking Packet Structure
6.7 Coordinate Frames

Three dimensional geometry is, in general, complicated and can lead to much confusion. The goal of this section is to avoid as much confusion as possible by fully defining the various cartesian reference frames or coordinate frames used in the Series2 system.

6.7.1 Camera Coordinates

By default, the Series2 system records all marker measurements in the camera’s coordinate frame (equivalently, in camera coordinates). The camera coordinate frame has its origin at the focal point of the lens. The Y axis points up, or from the bottom of the CLU base to the top of the camera body. The Z axis points outward along the optical axis of the camera lens. The X axis completes a right-handed coordinate frame and points left.

![Camera Coordinate Frame](image_url)

Figure 38: Camera Coordinate Frame

6.7.2 Marker Coordinates

Each marker has its own coordinate frame, owing to the 6 DoF measurement capabilities of the Series2 system. The origin of the marker coordinate frame is at the center of the starburst, shown as a blue dot in Figure 39. The Y axis points along the principal lobe of the starburst; it is the only starburst lobe that aligns with one of the four circular landmarks. The marker coordinate Z axis points out of the page in Figure 39, while the X axis points to the right, completing a right handed coordinate frame.
6.7.3 Room Coordinates

Section 4.10 covers the UI aspects of setting up a room coordinate system. This involves measuring three points with a pointing tool: The room coordinate frame origin, a point along the X axis, and a point in the XY plane. The room coordinate frame Y axis is created by orthogonalizing the vector from the origin to the point on the XY plane with respect to the X axis. The Z axis is given by the cross product of the X and Y axes, such that the room coordinate frame is right handed.

If a room coordinate frame is created on a level surface, the Z axis will point upwards.

6.7.4 Force Plate Coordinates

Section 4.11 covers the UI aspects of creating a force plate coordinate system. This involves pressing the pointing tool on the force plate at three non-collinear points. Since these points are measured in both force plate coordinates and camera coordinates, a transform between the two coordinate frames is calculated directly without special knowledge of either coordinate system. As a result, the force plate coordinate system may be different depending on the make and model of the force plate in question. Refer to the force plate datasheet or manual for definitive information.