Moiré Phase Tracking System User Manual

Model MT 384ib

Metria Innovation, Inc.

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1 Introduction

Moiré Phase Tracking™, or MPT, is a single-camera 3D motion tracking technology that operates with a passive cooperative marker. An MPT motion tracking system comprises

1. One or more moiré phase tracking markers (figure 1),
2. An MPT camera-lighting unit, or CLU (figure 2),
3. A Bolt-II MPT processing computer (figure 3),
4. Camera-lighting unit power supply.

The MT 384ib is described in this manual. The MT 384ib processes streaming images from the MPT camera-lighting unit, tracks one or more tracking markers and produces UDP packets with measurement results. Additionally, log files are produced.

Some characteristics of MPT are:

- Operation from a single camera, eliminating multi-camera calibration.
- Automatic tracking of multiple markers.
- Real-time tracking.

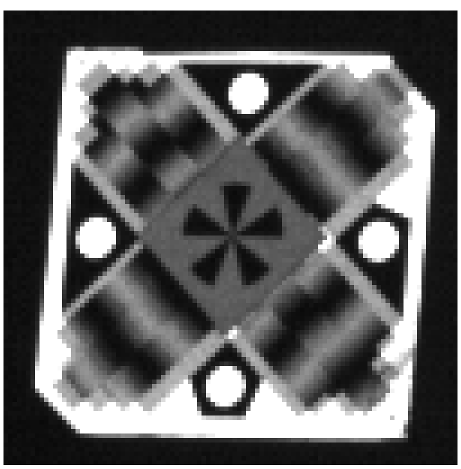


Image of 65mm MPT marker

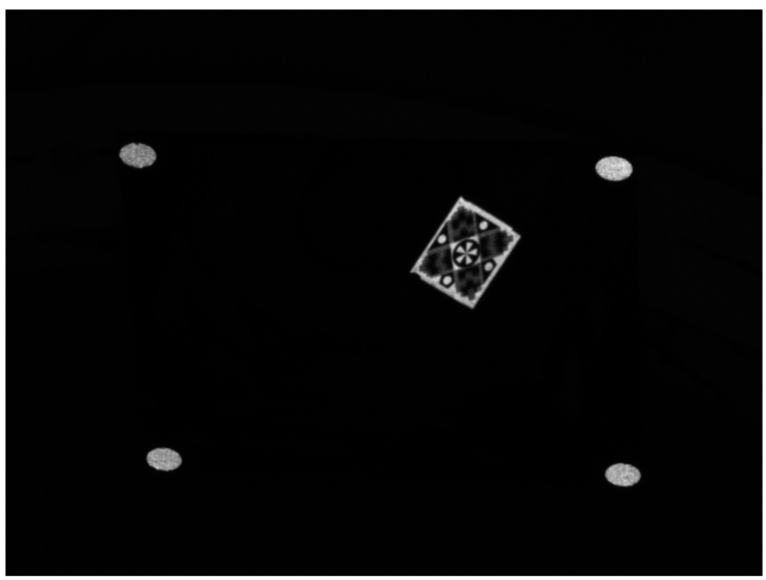


Image of 20mm MPT marker at 2.5 meters, through mirror.

Figure 1: An MPT image with marker.

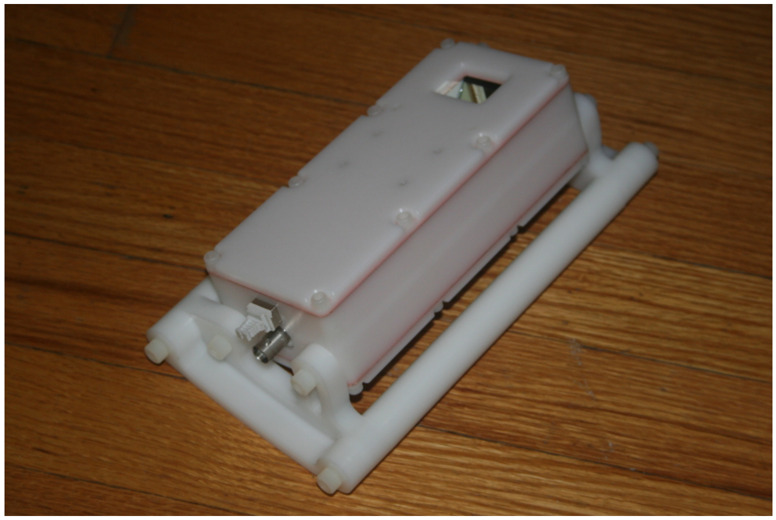


Figure 2: MPT camera-lighting unit.

Figure 3: Bolt-II moiré Phase tracking processing computer.

1.1 Overview of this manual

The quick start guide follows in section 2, followed by an introduction to the theory of operation of the MPT system in section 3, detailed user manual in section 4, MPT system adjustments in section 5 and trouble shooting guide in section 6. The appendices, section 7, detail notation and MPT configuration files.

2 Quick Start Guide

2.1 Starting the MPT hardware

2.1.1 Cabling

- Make the data connection between the MPT camera-lighting unit and the MPT computer. In the MT 384ib this is done with fiber optic.
  - The fibre and power connections to the CLU-384ib are seen in figure 4.
    1. Remove and save the fiber optic plug from the CLU fiber optic connector. Use this plug to prevent ingress of foreign matter when ever the CLU is not connected to fiber,
    2. Connect the fiber optic cable,
    3. Connect the coax power cable,

    Note: for high-field applications, both the fiber optic cable and coax have one low-susceptibility termination.
- Connect the fiber-optic cable to the Bolt-II computer, as seen in figure 5. Remove and save the fiber optic plug from the Bolt-II fiber optic connector. Use this plug to prevent ingress of foreign matter when ever the Bolt-II is not connected to fiber.
- Make power, network, monitor, keyboard, video and mouse connections to the Bolt-II.
  - Power is required.
  - Network is required to transmit UDP packets.
  - Video is required to preview images, such as for aligning the CLU camera.
  - Keyboard and mouse are required if optional interaction with MPT images, processing or log files is desired.

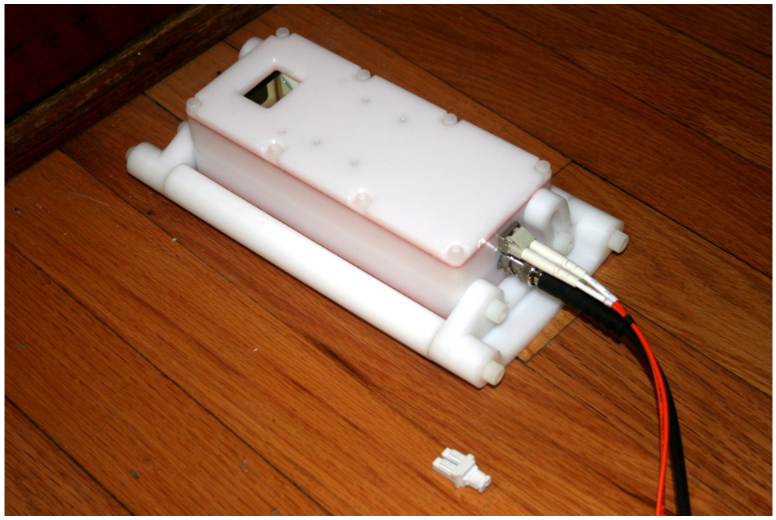


Figure 4: Cable connections to the CLU-384ib camera-lighting unit.

Figure 5: Back panel of Bolt-II computer, showing cables.

2.1.2 Logging-in to the Bolt-II MPT processing computer

- Energize the Bolt-II MPT processing computer.
- Power on: depress the circular button on the front of the Bolt-II.
- To shut down
  - With video and mouse: select "user" in the upper right corner of the screen, select "shutdown"
  - Without video and mouse: depress the power button.

2.1.3 Energizing the MPT Camera-Lighting

- Connect the camera-lighting unit by coaxial cable to the CLU power supply.

2.2 Starting the MPT Software

The MPT processing computer runs the Preempt_RT real-time variant of Fedora Linux. When it is booted, UNIX/Linux commands may be typed at a command prompt, and many operations are accessible through the drop-down menus accessed along the upper toolbar, seen in figure 6.

2.2.1 Automatic MPT software startup

- On boot-up, the MPT processing computer will launch X-windows, the Linux graphical interface, and launch MPT processing in the default processing configuration. The default processing configuration is set in file `ConfigRunTime.xml` (described in chapter 4 and appendix 7.2). The desktop configuration at startup is seen in figure 6.

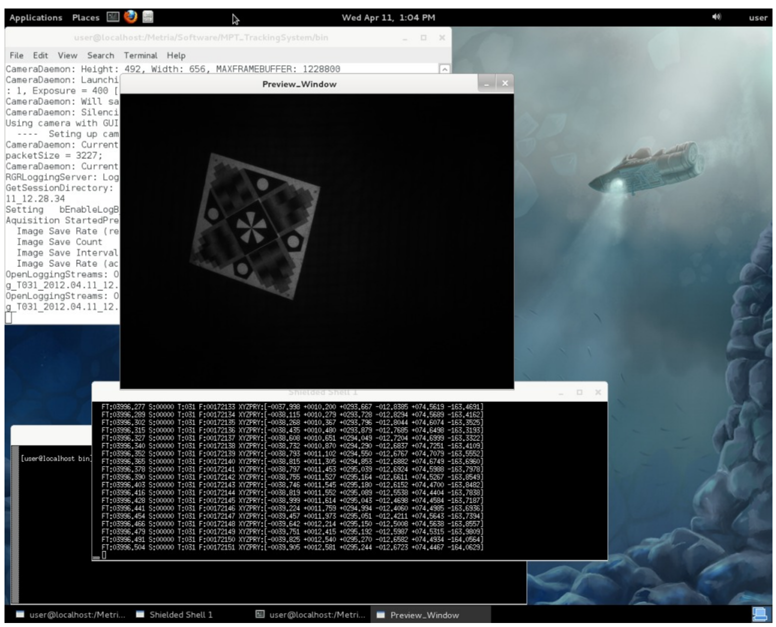


Figure 6: Screen shot of the Bolt-II computer upon booting. Program `TrackMPT_Marker` is automatically launched.

  - The program `CameraDaemonFW` runs in the upper left (described in chapter 3 and section 4.1)
  - The image preview window is seen above the CameraDaemon window.
  - Two black terminal windows are seen in the in lower left. Each is a Linux shell (bash) running on a shielded core (described in section 2.2.3.1). These windows are referred to as the "shielded core windows."

– The program `TrackMPT_Marker` is launched in the upper shielded core window (described in chapter 3 and section 4.2)

Following boot-up, the moiré phase tracking system is running in the default configuration and emitting UDP packets. When a recognized MPT marker is visible in the image, measurements will stream on the screen, in the graphing window, if activated, in the UDP packets.

Caution: The MPT system logs measurement data, as well as exceptions and images under certain circumstances (see sections 3.1.3.1 and 4.6). If the logging partition is over-full, the MPT system will prompt the user to purge the logging partition or exit. See section 4.6.3 for more detail.

2.2.2 Exiting MPT software, following automatic startup

- To exit MPT processing: type ^C or ^\ in the MPT processing terminal window (the black window).
- To exit CameraDaemonFW: type 'q' in the preview window or type ^C or ^\ in the CameraDaemon terminal window.

2.2.3 Manual startup

The Bolt-II boots to the default processing configuration, set in file ConfigRunTime.xml. However, many of the features described in the detailed user manual (chapter 4) are accessible by manually starting the two programs

- `CameraDaemonFW`
- `TrackMPT_Marker`

Manual startup is described in this section. Only one instance of `CameraDaemonFW` can can run at a time. And it is generally best to start `CameraDaemonFW` first and then `TrackMPT_Marker`. So before either program can be manually started, any existing instance must be exited, as described in section 2.2.2.

2.2.3.1 Setting up shielded cores for MPT processing

- The system will run at optimal performance when the moiré phase tracking process (or processes) execute on a shielded core (or cores). Shielded cores are CPU cores in the multi-core CPU that are dedicated to specified processes. Access to the shielded cores is gained with the command `LaunchProtectedXterms`:

```
[user@localhost ~] cd /Metria/Software/Scripts
[user@Bolt-II Scripts]$ ./LaunchProtectedXterms
```

The `LaunchProtectedXterms` creates two shielded CPU cores and launches an xterm in each, creating two shielded core windows, as seen in figure 6. A processes started in one of these windows will be effectively the only process using the corresponding CPU core, providing reliable real-time performance.

2.2.4 Bringing up the MPT Camera

Images are transferred from the MPT Camera to computer memory by program `CameraDaemonFW`.

- `CameraDaemonFW` may be launched using a non-shielded core.
- To activate the MPT camera, navigate to the /Metria/Software/MPT_TrackingSystem/bin directory.

```
[user@Bolt-II ~]$ cd /Metria/Software/Scripts/MPT_TrackingSystem/bin
```

- Launch program `CameraDaemonFW`.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW <options>
```

For example :

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -vpg -F 50 -E 123
```

CameraDaemon is configured via command line options that are described fully in section 4.1. The command line options in the example above are:

-v: Verbose option causes CameraDaemon to display status and diagnostic messages.

-p: Preview Window option launches an image preview window that will display the current captured image.

-g: Graphics option launches a window for graphical display of measurement data (x, y, z, pitch, roll, yaw).

-F 50: The frame rate will be set to 50 fps.

-E 123: The exposure time to 123 μs.

The values of 50 fps and 123 μs are used here as examples. See section 5 for a discussion of exposure and light level.

- To stop CameraDaemon, type ctrl-c in the terminal window where it was started or press the 'q' key in the preview window :

```
<ctrl-c>
```

2.2.5 Bringing up the moiré phase tracking software

- To activate moiré phase tracking, use one of the black shielded-core window created by `LaunchProtectedXterms`.
- Using the shielded core, navigate to the bin directory

```
[user@Bolt-II ~]$ cd /Metria/Software/Scripts/MPT_TrackingSystem/bin
```

- Launch program `TrackMPT_Marker`

```
[user@Bolt-II bin ]$ ./TrackMPT_Marker <options>
```

  - Program `TrackMPT_Marker` option examples

```
[user@Bolt-II bin ]$ ./TrackMPT_Marker
[user@Bolt-II bin ]$ ./TrackMPT_Marker -T 25
[user@Bolt-II bin ]$ ./TrackMPT_Marker -T 25 -S 1021
```

  where 1021 and 25 are the Marker Series Number and Physical Marker ID Number of a marker. (See section 4.8 for a description of marker numbering).

- `TrackMPT_Marker` should now be running, as illustrated in figure 6.
- To run a second `TrackMPT_Marker` process, use the second shielded-core window and launch a second instance of program `TrackMPT_Marker`.
  - In the second shielded xterm, change directory to the MPT system executable directory:

```
[user@Bolt-II ~]$ cd /Metria/Software/Scripts/MPT_TrackingSystem/bin
```

  - Launch `TrackMPT_Marker`:

```
[user@Bolt-II bin ]$ ./TrackMPT_Marker <options>
```

  - The second `TrackMPT_Marker` instance can run on the same or a different tracking marker.
    - If the second `TrackMPT_Marker` instance runs on different Marker ID Numbers, the two `TrackMPT_Marker` processes will process each image and report their respective measurements.
    - If the second `TrackMPT_Marker` instance runs on the same Marker ID Number, the two `TrackMPT_Marker` processes will process alternate images, permitting tracking at high frame rate.
- To stop `TrackMPT_Marker`, type <ctrl-c> in each processing window.

```
<ctrl-c>
```

- See section 4.2 for additional information regarding `TrackMPT_Marker` execution.

3 Theory of Operation

The theory of operation of the MPT system is described in this section. Real-time moiré phase tracking described in section 3.1, followed in subsequent sections by discussion of UDP packet generation, logging and other specific aspects of moiré phase tracking.

The basic steps of processing an MPT marker image are:

1. Detect and locate the starburst landmark
2. Detect, locate and classify the four circular landmarks
3. Make an initial estimate of the marker pose (`PoseHat1`) based on the five landmark locations in the image.
4. Using the `PoseHat1`, read the moiré patterns and fit a sinusoidal function to the intensity pattern.
5. Using the moiré-pattern phases, landmark locations and `PoseHat1`, estimate the marker pose (`PoseHat2`).
6. Report results, emit UDP packet and queue logging messages.

The next sections elaborate on some of the details.

3.1 Real-time Moiré Phase Tracking

In this section, the detailed operation of the real-time moiré phase tracking system is described. A block diagram giving an overview of the real-time system is seen in figure 7.

3.1.1 Basics of POSIX shared memory and message queues

The POSIX software standard provides a range of inter-process synchronization and communication tools. Several aspects are discussed here that are important for understanding the operation of `CameraDaemonFW` and `TrackMPT_Marker`.

Shared Memory Once a shared memory segment is created, it is accessed by multiple processes using a commonly known key. Each of the connected processes sees the shared memory segment. The UNIX ownership and protection model applies, and processes can connect with read or read/write privileges. A shared memory allocation persists until it is detached by all attached process. Shared memory can be detached under program control, for example during a clean shutdown, or by terminating all attached processes.

Message Queues: POSIX message queues can be used for both communication and synchronization. Message queues have UNIX ownership and permissions. Each message itself is a string of character data, which can be cast to a structure type known to both the sender and receiver.

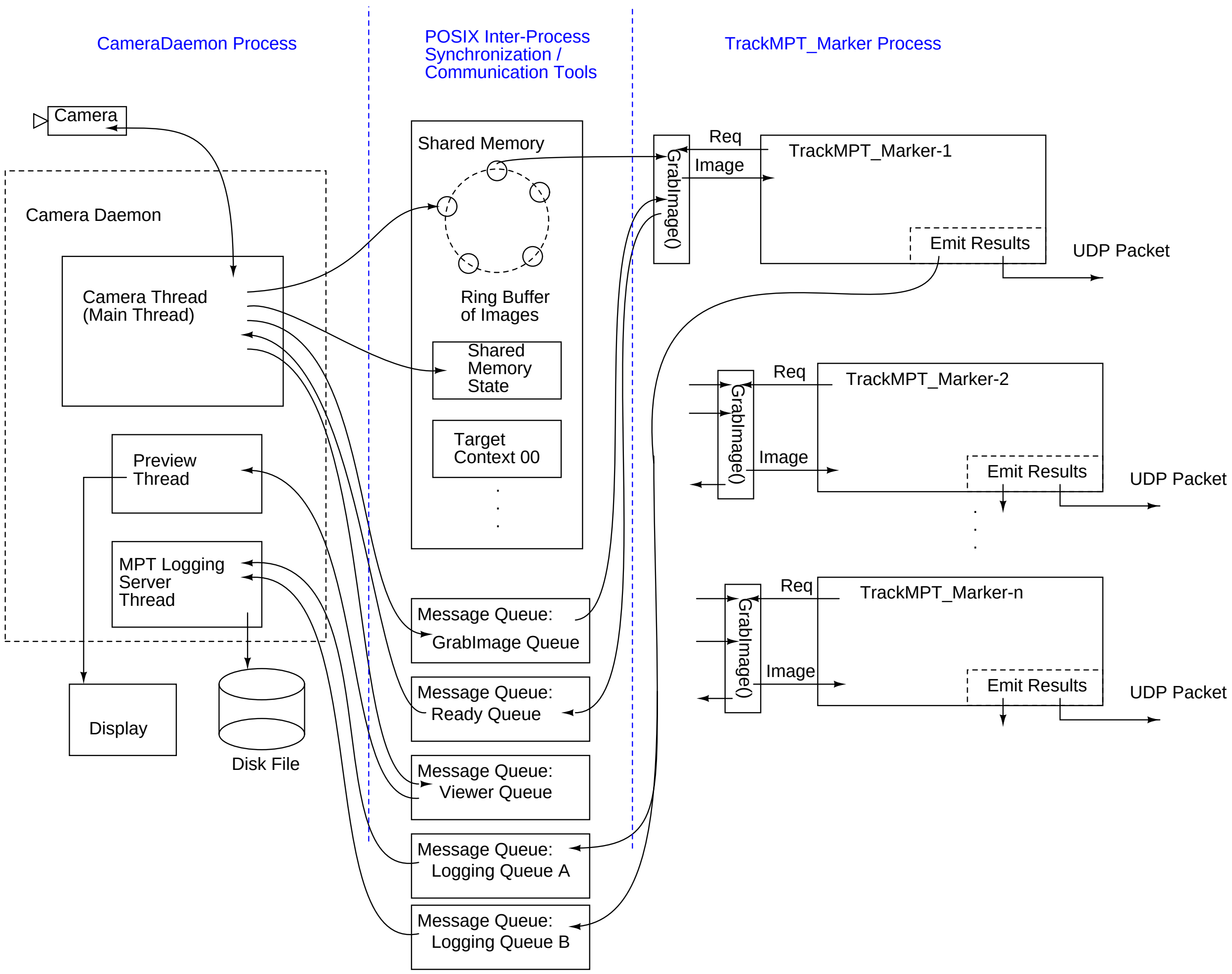


Figure 7: Block diagram showing overview of the real-time MPT system showing CameraDaemon and the MPT tasks.

When the message receive function is called with the appropriate flags, the calling process will sleep until a message is available, implementing inter-process synchronization. For example, when `TrackMPT_Marker` is running in each of two sessions, each will wait for a message on the GrabImage queue. If two or more processes are waiting, the operating system selects one to receive the message.

Semaphores: The wait and post mechanisms of POSIX semaphores make it possible to assure that only one process at a time enters a critical section of code. Only global semaphores appear with the ipcs command, described below.

Handy UNIX commands for managing shared memory, message queues and global semaphores:

ipcs: provides information on inter-process communication facilities. This command lists :

- Shared memory segments
- Global semaphores

- Message queues

Command `ipcs` can be used to see currently allocated shared memory segments, global semaphores and message queues. When MPT is running, one shared memory segment and several message queues are visible.

X-Windows also uses several shared memory segments and message queues that are visible with `ipcs`.

ipcrm: remove shared memory segments, semaphores and message queues. This can be useful if `CameraDaemonFW` or `TrackMPT_Marker` dies uncleanly, and leaves resources dangling.

Note: launching and exiting CameraDaemon also re-initializes the inter-process communication resources, as does rebooting the computer.

3.1.2 Operation of CameraDaemon

The CameraDaemon process launches several threads, including the Camera thread, Preview thread, Graphics thread and MPT Logging Server thread. The threads execute independently.

The camera thread communicates with the camera, setting the camera configuration and receiving images. When an image is received, these steps are executed:

- The image is transferred to the next node on the Ring Buffer, which is seen in figure 7.
- A message is sent to the GrabImage message queue, where the image can be consumed by a waiting `TrackMPT_Marker` process.
- If previewing is active, a message is sent to the preview thread, to indicate that an image is available.

3.1.3 GrabImage()

Function `GrabImage()` provides images to the running `TrackMPT_Marker` processes, and provides synchronization to the stream of images.

An `TrackMPT_Marker` process posts a read on the GrabImage message queue. This read will wait until an image is available. If there is an unprocessed image at the head of the ring buffer, GrabImage() returns the image immediately. If the last image on the ring buffer has already been accessed, GrabImage() will wait for a new message on the GrabImage queue.

For example, in figure 7, if processes `TrackMPT_Marker`-1 and `TrackMPT_Marker`-2 are configured to process the same marker, the `TrackMPT_Marker` / GrabImage() mechanics will insure that each image is processed only once. Additionally, if a `TrackMPT_Marker` process is ready, it will be started as soon as an image becomes available in the CameraDaemon ring buffer, minimizing temporal jitter.

3.1.3.1 CameraDaemon saves the ring when tracking is lost CameraDaemon detects a period of active image transfers via GrabImage() followed by a halt in image transfers. Exploiting the ring buffer architecture of figure 7, when a halt in image transfers is detected, CameraDaemon saves *nRingNodes*-1 images to disk, in the /Metria/Logging directory, as described in section 4.6.

This feature can be disabled (the default is enabled) with the -r option to CameraDaemon.

A period of active image transfer is defined as more than `GrabThreshold` consecutive transfers via `GrabImage()`. Parameter `GrabThreshold` is set in file `ConfigRunTime.xml` (see section 7.2).

3.1.4 Marker Context

An MPT Marker Context is a data record in shared memory that is accessed by `TrackMPT_Marker` processes. The marker context is specific to the Marker ID Number, and all `TrackMPT_Marker` processes processing a specific marker access the marker context of that marker. Communication with the marker context is illustrated in figure 8. The marker context supports:

- Tracking, so each `TrackMPT_Marker` process benefits from the most recent tracking information available in all `TrackMPT_Marker` processes.
- Estimation, so each `TrackMPT_Marker` process benefits from the most recent measurements from all `TrackMPT_Marker` processes.

3.1.5 Marker tracking and prediction

Moiré phase tracking operates by

1. Applying a first-order spline to the most recent two locations of the marker, to predict the current location, followed by
2. Searching for the MPT marker in the neighborhood of the predicted location.

To support marker tracking:

- When markers are detected and identified by their specific Marker ID Number, their location is recorded in the marker context with a call to function `RegisterMarkerLocation()`, seen in figure 8.
- When an image is passed to a `TrackMPT_Marker` process via `GrabImage()`, the predicted marker location is also provided. Prediction is done with a first-order spline fit to the two most recent measured marker locations. Testing on a range of spline orders and supports has shown that a first-order spline on a two-point support gives the highest probability of marker detection at the predicted location, perhaps because of the high accelerations sometimes present in human movement.

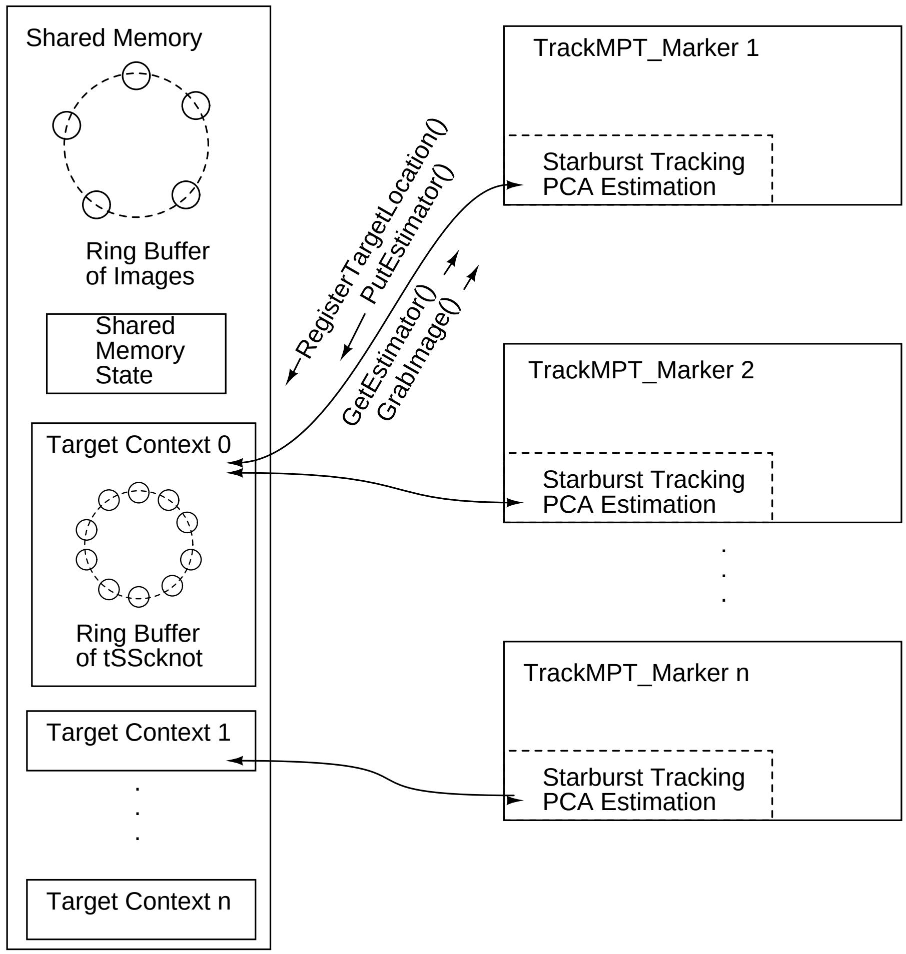


Figure 8: Block diagram of the real-time MPT system showing marker contexts in shared memory.

3.1.6 The cosine ambiguity recovery mechanism

As describe at the beginning of section 3, in MPT processing an initial estimate of pose, called `PoseHat1`, is determined from landmark locations.

In the region near "top-dead-center," where the line-of-sight from the marker to the camera is nearly perpendicular to the marker surface, the estimation of `PoseHat1` from the landmarks is poorly conditioned and there is considerable uncertainty in the initial estimate of the out-of-plane rotations. This uncertainty plays only a small role in the subsequent reading of the moiré patterns. But if the error in the initial estimate of out-of-plane rotation is too great, the final pose estimator may find an incorrect solution when matching the moiré patterns. To increase robustness in this region, tracking information is used to further constrain the pose estimate. The cosine ambiguity recovery mechanism compares the current estimates of `PoseHat1` and `PoseHat2` with tracking information, and select a solution that is consistent with the tracking information.

The cosine ambiguity recovery mechanism can be activated or de-activated by setting `bEnableCosineAmbiguityRecovery` to true or false in file `ConfigRuntime.xml` (see section 7.2).

Cosine ambiguity recovery is rarely required.

3.1.7 Accelerated Starburst detection

For detection, the starburst landmark of an MPT marker must have an intensity above a threshold level. To accelerate detection of the starburst landmark, a minimum intensity threshold is set, and regions below this threshold are not searched.

The threshold is set by parameter `StarburstPreSearchIntensityThreshold` in file `ConfigRunTime.xml` (see section 7.2).

3.1.8 Automatic detection of Physical Marker ID Number

The MPT system can automatically detect and track a recognized marker, as described in this section. First manual declaration of the Marker ID Number is described, then automatic detection.

Manual declaration of the Marker ID Number.

```
bEnableAutoMarkerDetect = false
```

When `ConfigRunTime.xml` parameter `bEnableAutoMarkerDetect` is set to false, program `TrackMPT_Maker` will look in each image for the Marker ID Number given in `ConfigRunTime.xml` or on the command line. If a different marker is presented, it will not be recognized.

Automatic detection of the Marker ID Number.

```
bEnableAutoMarkerDetect = true
```

When `ConfigRunTime.xml` parameter `bEnableAutoMarkerDetect` is set to true, with some restrictions program `TrackMPT_Maker` will identify a new marker presented to the camera, and automatically begin to track that marker. Automatic detection and tracking occurs when

- There is only one marker present in the image,
- Only one `TrackMPT_Marker` process is running,
- A calibration file for the presented marker is included in the system installation,
- The Marker Series Number of the marker is either the primary or secondary Marker Series Number (see section 4.8).

When multiple `TrackMPT_Marker` processes are running, either on different markers or for alternate-image processing of a given marker, automatic detection of the marker ID number should not be used.

3.1.9 Frame and Interrupt time stamps.

CameraDaemon provides a mechanism to record the times of external events, these times can be used to correlate those external events with image exposure. The external event is brought into the Bolt-II via a parallel port adaptor, which responds to the rising edge of a TTL signal. The rising edge TTL signal will cause an interrupt on the Bolt-II to register the Interrupt Time Stamp, and increment a counter (*irqSequenceNum*). The Interrupt Time Stamp (*irqTime*) along with the end of exposure time stamp (*frameTime*) and *irqSequenceNum* are all available via the UDP packet.

- Two timing measurements are provided in the UDP packet generated by MPT system. Both measurements are provided in two parts, seconds and nanoseconds (see section 3.2).

1. Frame Time Stamp (*frameTime*)- This is the time at the center of the frame exposure. The frame time stamp is given by:

   `frameTime = Tframe_arrival - frameDelay_uS`

   where

   Tframe_arrival is the Bolt-II system-wide clock time when `CameraDaemon` received the frame,

   – *frameDelay_uS* is a value loaded from `ConfigRunTime.xml`, and can be used to offset `Tframe_arrival` to the end of the exposure.

     * GC-650 gigabit-ethernet camera: a *frameDelay_uS* value of 10393 μs has been calibrated for a operating at maximum frame rate.
     * Stingray F033B firewire camera: a *frameDelay_uS* should be set to zero for the (the firewire camera driver provides the exposure time as measured by the Linux clock in the low-level image data structure).

2. Interrupt Time Stamp (*irqTime*)- This is the time of the last externally triggered event detected by the Interrupt-Time-Stamp driver.

   `irqTime = Tirq_registered - irqDelay_uS`

   where

   irqTime is the time of externally triggered event to

   Tirq_registered is the time the MPT computer recorded the interrupt

   irqDelay_uS is the time delay from the rising edge of the interrupt to registration of Tirq_registered.

   irqSequenceNum is a counter that is incremented each time an interrupt is received.

   (The default value of 8 μs listed, listed in section 7.2, has been calibrated for a Bolt-II computer.)

3.2 UDP packet format

- The UDP packet format, version 3 is listed.
  - Integers, Unsigned Integers and floating point numbers are 32 bits.
  - A value of status=0 indicates a valid reading.

```
#define CURRENT_PACKET_VERSION_NUMBER 3
typedef struct UDPPacketDef_s {
  int PacketVersionNumber;
  int status;
  int MarkerIDNumber; (formerly TargetIDNumber)
  int FrameNumber;
  float x,
        y,
        z;   /* z is filtered */
  float qr,  /* quaternion real part   */
        qx,  /* quaternion vector part */
        qy,
        qz;
  unsigned int frameTime_sec;
  unsigned int frameTime_nsec;
  unsigned int irqSequenceNum;
  unsigned int irqTime_sec;
  unsigned int irqTime_nsec;
  float tSScknot[6];
  float tZcknotHat;
  float xHat,   /*  x, y, z based on the estimated sZ */
        yHat,
        zHat;
} UDPPacket_t ;
```

3.3 The session directory for logging

Every time CameraDaemon is launched it creates a new session directory at the path:

```
/Metria/Logging/Session-<Session Date&Time>/
```

where <Session Date&Time> is a unique identifier based on the date and time of the CameraDaemon activation. For example:

```
/Metria/Logging/Session-2010.11.03_17.17.49
/Metria/Logging/Session-2010.11.03_17.17.09
```

When loaded, the shell function `GoToMostRecentMPTSession` will take the current working directory of a shell to the most recent session directory. For example:

```
[user@Bolt-II ~]$ GoToMostRecentMPTSession
[user@Bolt-II Session-2010.11.03_17.17.49]$
```

3.4 Maximum range and required image size for moiré phase tracking

3.4.1 Maximum range

The maximum range for marker tracking is defined by two effects:

- Focus and depth of field, and
- Minor radius of the ellipse enclosing the starburst.

MPT is robust to several pixels of blur, but blur at the level of 4-5 pixels will prevent processing of the marker.

The minor radius of the ellipse enclosing the starburst landmark must be at least 11 pixels. The landmark is foreshortened by tilt, and so the maximum geometric range is greater when the marker is in near normal orientation to the camera, and becomes less as the tilt increases.

3.4.2 Range and tilt fore-shortening of the MPT marker

The image of an MPT marker is fore-shortened by tilt, as seen in figure 9. The tilt angle is given by

$$\theta_t = \cos^{-1}\left(\left\langle \overline{Z}_{\{\mathring{t}\}}, \overline{Z}_{\{\mathring{c}\}} \right\rangle\right) \tag{1}$$

where $\left\langle \overline{Z}_{\{\mathring{t}\}}, \overline{Z}_{\{\mathring{c}\}} \right\rangle$ is the inner product of the camera and marker unit Z-axis vectors.

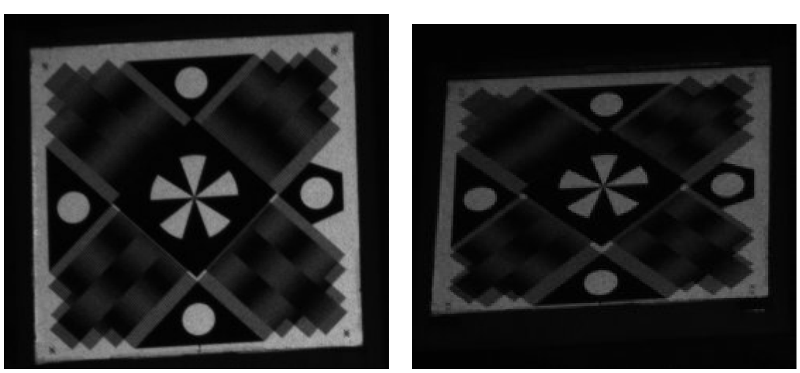


Figure 9: Illustration of marker 006, nearly straight-on and at 40 degrees of tilt.

The degree of fore-shortening determines the required pixel footprint of the marker in the image. Tilts up to 60^o are accommodated when the image resolution would provide 65 pixels along the nominal length of one edge of the marker. For example,

Nominal marker size:	$L_1 = 20\,\text{mm}$
Camera Resolution:	$s_x = 0.0074\,\text{mm/pixel}$
Distance:	$L_2 = 2800\,\text{mm}$
Effective Lens Length:	$c_p = 70.0\,\text{mm}$

gives:

$$(1/s_x)\,(c_p/L_2)\,L_1 = \tag{2}$$

$$(1/0.0074)\,[\text{pixels/mm}] * (70/2800)\,[\text{mm/mm}] * 20\,[\text{mm}] = 67.6\,[\text{pixels}] \tag{3}$$

so in this configuration, the marker could be tracked to tilt angles slightly over 60^o.

At lower image resolutions, the marker may still be tracked, but not up to 60^o of tilt. The maximum tilt is given according to:

$$\theta_t = \cos^{-1}\left(\frac{65\cos(60^o)}{(1/s_x)\,(c_p/L_2)\,L_1}\right) \tag{4}$$

For example, with the above data a 12mm marker can be tracked up to a tilt angle of

$$\theta_t = \cos^{-1}\left(\frac{65\cos(60^o)}{(1/0.0074)\,(70/2800)\,12}\right) = 36.7^o \tag{5}$$

3.5 Measurement coordinate frames

MPT measures the pose of the marker in the camera coordinate frame. The imager, camera and marker coordinate frames are illustrated in figure 10.

Camera frame: The position of the camera coordinate frame is defined by the lens of the camera. The Z axis of the camera frame, ${}^cZ$, lies along the optical axis of the lens and the origin of the camera coordinate frame is centered at the lens "object-side principal point." Because it is defined by the optical properties of the lens, and will often be within the lens, it is not generally possible to mechanically locate the principal point.

Marker frame: The marker coordinate frame is attached to the front face of the maker as seen in figure 11, with the origin of the marker coordinate frame centered on the starburst landmark. The Y axis is aligned with the key spoke of the starburst landmark, the X axis lies in the plane of the marker, and the Z axis is directed outward from and normal to the marker front face. The key spoke is the starburst spoke (one of the five seen in figure 11) that aligns with a circular landmark.

In figure 10, note the 180^o yaw-axis rotation between the camera and marker coordinate frames.

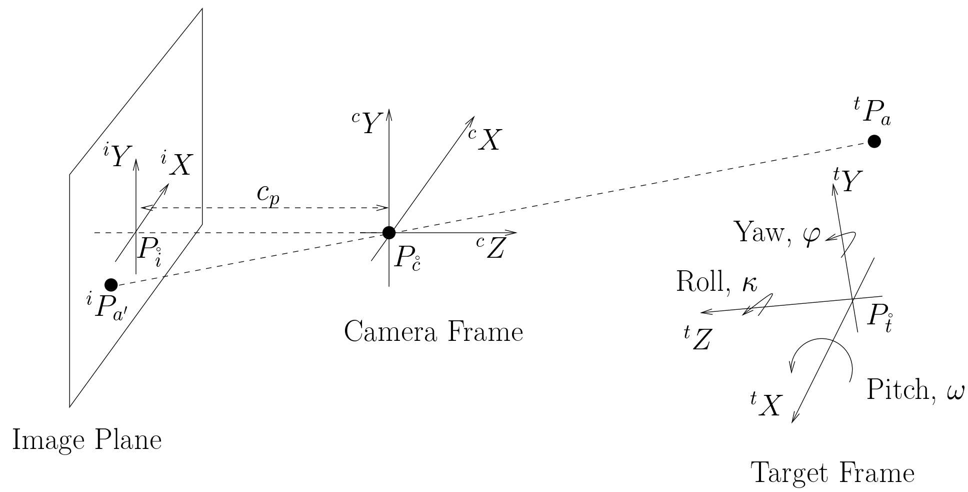


Figure 10: MPT measurement coordinate frames. A point ^tP_a in marker coordinates is show, along with the corresponding image point ^iP_a.

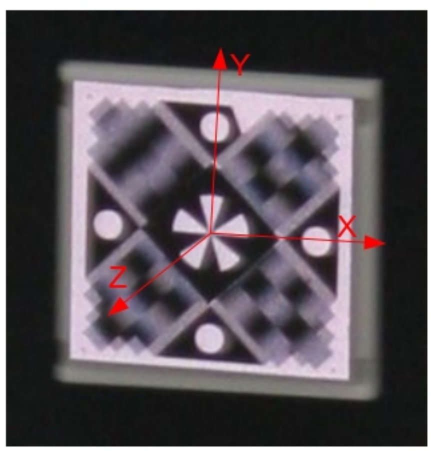


Figure 11: MPT motion tracking marker with X, Y and Z axes of the maker coordinate frame indicated.

4 Detailed User Manual

4.1 Camera Daemon

4.1.1 Basics of Camera Daemon

CameraDaemon is the C-language component of the MPT real-time system. The features intended for normal user operation are listed in this section. CameraDaemon related commands are run from a Linux shell, normally in either a gnome-terminal or xterm window.

Basic usage is as follows:

- Launch CameraDaemon
  - CameraDaemon should be executed from directory ./bin.

    ```
    [user@Bolt-II MPT_TrackingSystem ]$ cd bin
    [user@Bolt-II bin ]$ ./CameraDaemonFW
    ```

  - Note the './' preceding the CameraDaemon command. This tells Linux (UNIX) to take the command from the current working directory.
  - If the camera does not start, see section 6.1.

4.1.2 CameraDaemon help message

- CameraDaemon if executed with the '-help' option responds with the following text :

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -help
Usage:
  CameraDaemon  <options>
    -v          Verbose mode, messages printed describing operation.
    -V          Very Verbose mode, many messages printed describing operation.
    -? -help    This message.
    -F 20       Set Frame Rate to 20 fps.
    -R 2        Set Image Save Rate to 2 ips.
    -S 100      Set Image Save Count to 100 images.
    -U 5        Set UnderSample Rate to every 5th image.
    -E 1000     Set Exposure to 1000 micro-seconds.
    -D /tmp     Load Images from Directory.
    -T 24       Launch an RGR instance for marker 24.
    -p          Turn On Preview Window
    -c          Stream cropped images to disk files, cropped images centered
                on pHintXY received from TrackMPT_Marker().
    -g          Continuous graphing of logging data.
    -G          Report statistics when graphing updates.
    -r          Disable automatic saving of 6 images when tracking stops.
  Demo mode switches:
    -l          Continuously Loop from Directory (demo mode only).
    -n          Suppress looking for frame number in image file name
                (demo mode only).
    -w          Wait to load images until RGRs(s) are ready  (demo mode only).
  Preview window active keystrokes:
     i          Show maximum intensity.
     I          Preview binary image, painting pixels at maximum level white.
     J          Terminate preview binary image.
     s          Save next nImagesToSave images to disk.
     r          Save the ring buffer to disk.
     t          Read and report camera temperature sensor.
     h          Flip left-to-right the preview window.
     v          Flip top-to-bottom the preview window.
     q          Quit.  This will shut down CameraDaemon.
```

4.1.3 Verbosity

- There may be instances where knowledge of what CameraDaemon is doing may aid in development. Two separate levels of verbosity are available to print messages to the terminal window pertaining to CameraDaemon's current operation.
- Moderately verbose.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -v
```

- Highly verbose.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -V
```

- By default verbosity is off.

4.1.4 Frame Rate and Under Sample

- The frame rate can be set in `ConfigRunTime.xml` or set when running CameraDaemon using the -F flag. Frame Rate will set the the camera to take `FrameRate` images per second. A camera is limited to a peak frame rate, if the FrameRate parameter is set above the limit, a message will be displayed and the camera will default to its maximum frame rate.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -F 200
```

- The light on the MPT Camera and Lighting Unit will flash at the frame rate set for the camera. The Under-Sample option allows for synchronous acquisition of images at frequencies below what is acceptable for human subjects while maintaining an acceptable ring flash frequency. An under-sample rate set to N will provide the `TrackMPT_Marker` function with every N^{th} image coming from the camera. The default under-sample rate is 1. If you would like to process images at 30 fps but maintain a flash frequency of 60 Hertz you could run CameraDaemon with the following options :

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -F 60 -U 2
```

  - In this case every 2^{nd} image is provided to `TrackMPT_Marker`, and the other half of the images are discarded.

4.1.5 Image-save count and image-save rate

An 's' typed to the preview window launches image save (see section 4.1.7.1).

- The number of images to save can be set in `ConfigRunTime.xml` or set when running CameraDaemon using the -S flag. Setting this parameter on the CameraDaemon command line will override the default configured in `ConfigRunTime.xml` (see 7.2).

- The rate at which images are saved can be set when running CameraDaemon using the -R flag. Setting this parameter on the CameraDaemon command line will override the default configured in `ConfigRunTime.xml` (see 7.2). This is the image-save rate in images per second. Note : The system will provide a rate closest to the requested rate based on an integer divisor of camera frame rate. For example, if the camera is running at 60 fps and the user requests a image-save rate of 25 ips, the system will provide a image-save rate of 30 ips.

4.1.6 Exposure

- The exposure for each image taken by the camera is set in `ConfigRunTime.xml` or using the '-E' option. This option is specified in microseconds. The camera has upper and lower limits corresponding to this value. If set out of range a message will be produced and the value will be coerced into the acceptable range for the camera.

  ```
  [user@Bolt-II bin ]$ ./CameraDaemonFW -E 700
  ```

  An additional limit on the exposure time is placed by the thermal protection logic within the lighting system. Depending on the light level setting and the camera-flash duty-cycle, the protection logic may shut the lighting system down when it encounters a flash that exceeds the thermal protection limit.

4.1.7 Preview window

- The Preview Window displays images acquired by the camera. The Preview Window refresh rate is typically less than the camera frame rate, it skips images to always display the most recent frame. The preview window is activated with the `bShowPreviewWindow` parameter in `ConfigRunTime.xml` or the '`-p`' option

  ```
  [user@Bolt-II bin ]$ ./CameraDaemonFW -p
  ```

4.1.7.1 Hot-keys that operate in the preview window

- Several keys are detected when they are typed into the preview window. These provide mechanisms that can be selected while CameraDaemon is running. They are activated by typing the corresponding keystroke in the preview window.

  i: Show intensity

  Analyze the image and report the value of the brightest pixels and the number of pixels at that brightness. Pressing the hot-key toggles the display on and off.

  I: Show intensity II

  Render the image as a binary image, showing only the brightest pixels. Repeated keystrokes 'I' rotates through 7 modes

- Show intensity II, intensity threshold = 100% of maximum intensity
- Show intensity II, intensity threshold = 95% of maximum intensity
- Show intensity II, intensity threshold = 75% of maximum intensity
- Show intensity II, intensity threshold = 50% of maximum intensity
- Show intensity II, intensity threshold = 25% of maximum intensity
- Show intensity II, intensity threshold =12.5% of maximum intensity
- Show intensity II off

Show intensity and Show intensity II will aid in setting the lighting level that maximizes MPT marker contrast without pushing the marker into pixel saturation.

J: Terminate Show intensity II

The 'J' keystroke immediately shuts of Show intensity II.

m: Toggle preview and graphing window marking

q: Quit. This keystroke causes CameraDaemon to shut down.

r: save Ring. Provoke the save ring mechanism, which writes images on the image ring buffer out to disk.

s: Save images. CameraDaemon can save `nImagesToSave` images to disk, this is activated by typing 's' to the preview window.

While saving images, the preview window will freeze and display 'Saving Images'.

- The number of images to be saved is controlled by the CameraDaemon run-time parameter S or the parameter `nImagesToSave` in file `ConfigRunTime.xml` (see section 7.2).
- When the save-images action is complete, the images will be saved in directory

```
/Metria/Logging/Session-<Session Date&Time>/
                        SavedImages-<Instance Date&Time>/<FrameNumber>.bmp
```

The session date and time mark the time of the first capture by the current session of CameraDaemon. The instance date and time mark the date and time of the specific capture of images. Multiple collections of images can be saved during a single session.

t: Temperature. This hot-key toggles camera temperature display on/off. Note : Camera temperature is not supported for all cameras.

h: Flip the preview image horizontally (gives the mirror view rather than the tv view, may be good for grabbing camera calibration images).

v: Flip the preview image vertically (good for collecting camera calibration images via a mirror).

– Preview window will resume displaying images when saving is complete.

- During image saving, a second 's' typed to the preview window will terminate the saving action.

4.1.7.2 Preview and Graphing Window Marking Typing an 'm' with the cursor in the preview window toggles activation of "Preview and Graphing Window Marking". When "Preview and Graphing Window Marking" is active, white cross-hairs are drawn in the preview window, as seen in figure 12. Black '+'s are drawn at the edges of the graphing window, also seen in figure 12.

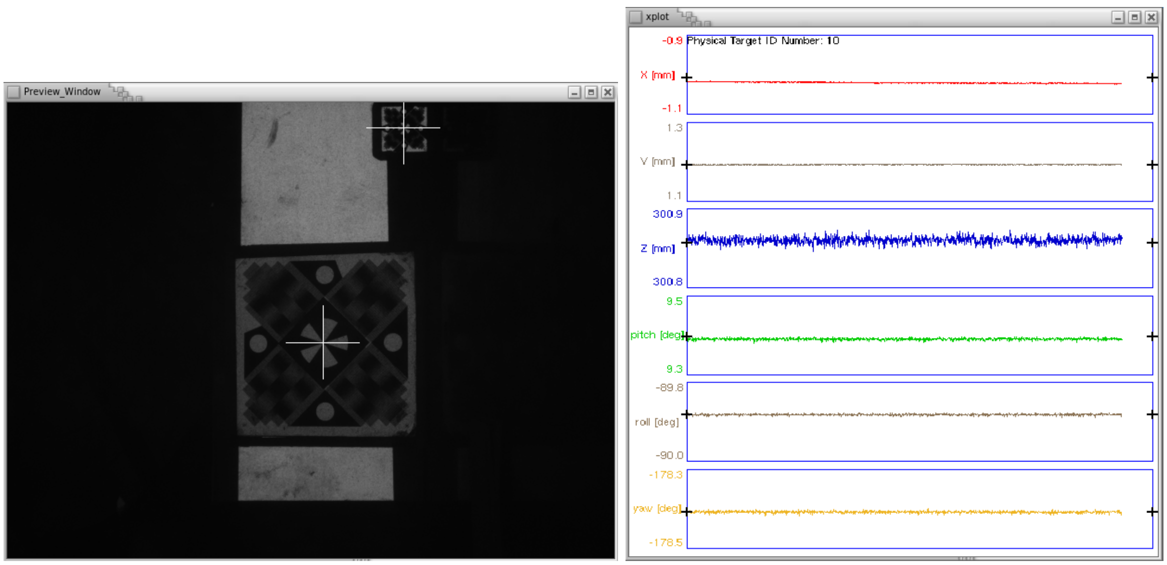


Figure 12: Preview and Graphing Windows with marked MPT markers.

Action of 'm' key-stroke:

- If 'm' is typed and "Preview and Graphing Window Marking" is off
  - If one or more MPT markes are currently being tracked: Activate marking, mark current location of MPT marker(s) in the preview image.
  - If there is no MPT marker currently being tracked: no action.
- If 'm' is typed and "Preview and Graphing Window Marking" is on: deactivate marking.
- To update marker location(s): type 'm' twice (toggle off then on).

As seen in figure 12, when tracking multiple markers, "Preview and Graphing Window Marking" will mark all markers in the preview window.

4.1.8 Graphing a continuous plot of the MPT marker pose

The graphing option will display a graph of X, Y, Z, Pitch, Roll and Yaw. The plot is automatically scaled according to the collected data. Graphing is launched with the `bShowGraphingWindow` parameter in `ConfigRunTime.xml` or with the -g option.

- [user@Bolt-II bin]$ ./CameraDaemonFW -g

Notice that graphing doesn't start displaying data until `TrackMPT_Marker` is running. See section 4.3 for additional details. The MPT Graphing window is illustrated in figures 13, and figure 16, below.

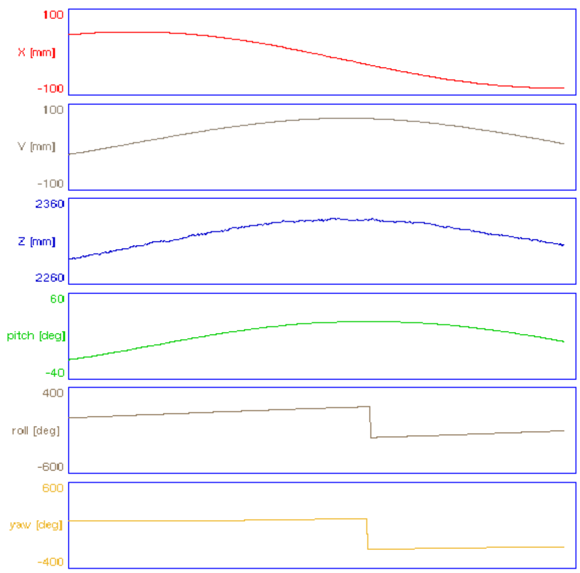


Figure 13: Illustration of the graphing window, showing marker pose plotted in Camera Cartesian coordinates.

- When graphing is active, statistics of the plotted data can additionally be viewed with the -G switch. See section 4.4.4.
- When Preview and Graphing Window Marking is activated, black '+' are drawn at the left and right edges of each axis in the graphing window, see section 4.1.7.2

The graphing window can only display data from one marker at a time. The marker displayed is the first detected in the current session.

4.1.9 Loading images from disk

- CameraDaemon provides a Demo Mode which does not require a camera. In Demo Mode images are loaded from disk instead of being streamed from a camera. Demo Mode is activated with the -D option followed by the path to a directory containing a set of images.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -D /tmp/Images
```

Additionally there are several options that can only be used with Demo Mode.

-l In normal operation, Demo Mode will serve up the images from a directory at the specified or default frame rate. Once the directory is exhausted, CameraDaemon exits. For continuous operation, Demo Mode / looping mode can be used to continuously loop through the set of images. Notice that the option is the letter l (ell) not the number 1 (one).

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -l -D /tmp/Images
```

-n To emulate a camera image stream, CameraDaemon extracts the right-most numeric portion of the image file name and uses it to produce the image frame number. To disable this feature and provide sequential frame numbers use the '-n' option:

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -n -D /tmp/Images
```

-w To enable processing every image in a directory, the waiting mechanism can be invoked using the '-w' option. CameraDaemon will wait until `TrackMPT_Marker` has processed each image before loading the next image.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -w -D /tmp/Images
```

4.1.10 Examples of typical CameraDaemon usage

- General usage for CameraDaemon usually involves setting the Frame rate and exposure, also it is nice to use Preview Window and Graphing

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -pg -F 80 -E 600
```

- It may be convenient for CameraDaemon to behave like the camera even though a camera is not present. "Demo Mode" is launch with

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -D /tmp/Images
```

- When loading images from disk, the '-w' options is used to throttle the images so each image gets processed.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -pgw -D /tmp/Images
```

- The '-l' option will cause CameraDaemon to loop through a set of image files continuously.

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -pgl  -F 80 -D /tmp/Images
```

- Also, notice that options can be listed individually and in any order. The example above can be changed to:

```
[user@Bolt-II bin ]$ ./CameraDaemonFW -F 80 -p -g -l -D /tmp/Images
```

4.2 TrackMPT_Marker

Program TrackMPT_Marker processes images to produce measurements. It is launched as described in sections 2.2. The broad theory-of-operation is given in section 3.1.3. Details of using program TarckMPT_Marker are provided here. The basic processing cycle of TrackMPT_Marker is illustrated in figure 14.

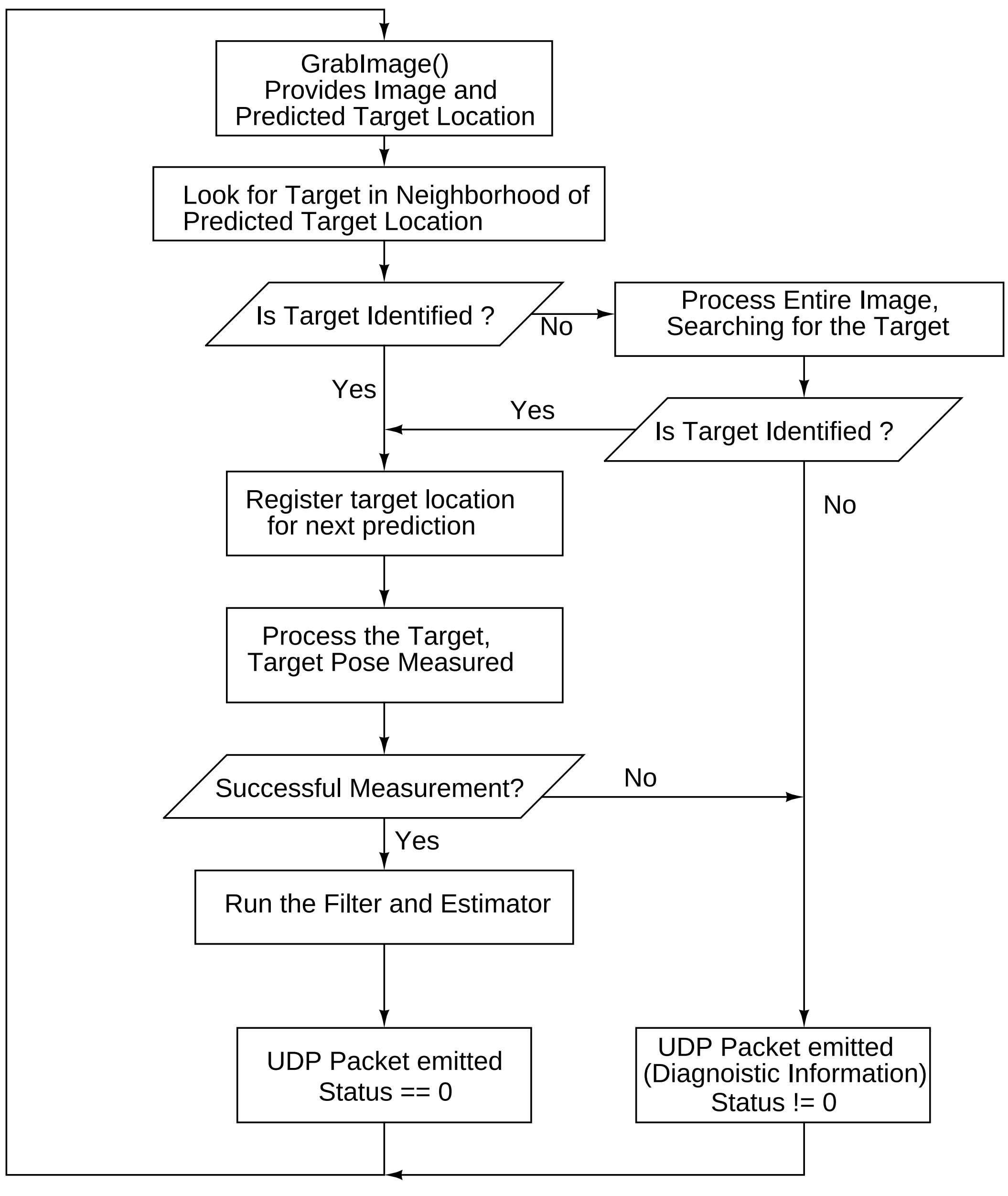


Figure 14: Basic processing cycle of program TrackMPT_Marker.

MPT Measurement proceeds in these steps:

1. Grab the image and predicted marker location with function `GrabImage()`.
2. Search for the marker
   (a) Search for the marker in the neighborhood of the predicted marker location,
   (b) If the marker is not identified at the predicted location, search the entire image.
3. If the marker is identified, process the marker.
4. If there was a successful measurement, run the filter and estimator.
5. In all cases, generate a UDP packet and logging entry. If processing is successful, the status is marked `status=0` in the UDP packet and logging entry.

4.2.1 Performance

On a Bolt-II computer, each MPT process is able to process approximately 100 frames per second average throughput. MPT processing has variable timing. For measurement rates above 80 measurements per second, it is recommended to process on two cores. Because of the variability in time required to process one image, processing on two cores will give the advantages of more reliable processing at the frame rate and reduced temporal jitter in the UDP packet timing.

MPT runs on the main path of figure 14 in approximate 10 milli-seconds. If marker tracking is lost and the entire image is searched, processing will be delayed for approximately 100 milli-seconds. Loss of tracking can be caused by fast motions or marker obstruction. When marker motion returns to an acceptable level, tracking will resume.

4.2.2 Filter and estimator

Two methods are provided to filter pose values or to estimate pose values:

1. A 5^{th} order digital filter
2. An estimation algorithm

MPT is very accurate for orientation and 2 elements of position, but relatively less accurate for the distance of the camera-marker separation, which is written ${}^{s}Z_{\mathring{c}}$ and is typically estimated with an accuracy of 1/2,000 the camera-marker separation.

The 5^{th} order digital filter can now be applied to all 6 pose elements in Camera Cartesian coordinates, ${}^{c}\mathcal{P}_{\mathring{t}}$. See section 7.1 for definition of the elements of pose vector ${}^{c}\mathcal{P}_{\mathring{t}}$.

4.2.2.1 Optional 5^{th} order discrete filtering of samples A 5^{th} order discrete-time filter is applied to each component of pose vector ${}^{c}\mathcal{P}_{\mathring{t}}$. That is to say, six parallel 5^{th} order filters are run. The filter mechanism, combined with parameters in

```
/Metria/Software/MPT_TrackingSystem/ConfigRunTime.xml,
```

provides these capabilities:

- Set the filter parameters,
- Enable / Disable filtering for each element of ${}^{c}\mathcal{P}_{\hat{t}}$, individually,
- Control when the filter state is initialized.

The filter is implemented according to

$$\begin{aligned} w_{out}(k) &= -A(2)\,w_{out}(k-1) - \ldots - A(6)\,w_{out}(k-5) \\ &\quad + B(1)\,w_{in}(k) + \ldots + B(6)\,w_{in}(k-5) \end{aligned} \qquad (6)$$

where k is the sample index.

Controlling filtering of individual parameters:

Vector of logical values `bRunFilter` controls whether an individual value in ${}^{c}\mathcal{P}_{\hat{t}}$ is filtered.

```
<bRunFilter> [true, true, true, true, true, true] </bRunFilter>
```

Set values to false to suppress filtering. The elements of ${}^{c}\mathcal{P}_{\hat{t}}$ are

$${}^{c}\mathcal{P}_{\hat{t}} = \left[\begin{array}{cccccc} \theta_x & \theta_z & \theta_y & {}^{c}X_{\hat{t}} & {}^{c}Y_{\hat{t}} & {}^{c}Z_{\hat{t}} \end{array}\right]^{T} \qquad (7)$$

See section 7.1 for definitions of the rotations.

Filter Parameters:

The filter parameters are set by setting `Bfilter` and `Afilter` in `ConfigRunTime.xml`. Example values are:
No filtering:

```
<!--   This is a 5th order "non-filter."  With these parameters,
       data are passed through without change, equivalent to turning off filtering.
 <Bfilter>            [1 0 0 0 0 0 ]  </Bfilter>
 <Afilter>            [1 0 0 0 0 0 ] </Afilter>
-->
```

Light filtering:

```
<!--   This is a 5th order Butterworth, wn = 1/3 (10 Hz with 60 Hz sampling)
       group delay ~= 5.5 samples
-->
 <Bfilter> [0.0106119   0.0530595   0.1061191   0.1061191   0.0530595   0.0106119] </Bfilter>
 <Afilter> [1.0000000  -1.6448489   1.5866151  -0.8048818   0.2299491  -0.0272522] </Afilter>
```

Heavy filtering:

```
<!--   This is a 5th order Butterworth, wn = 1/48 (0.625 Hz with 60 Hz sampling),  group delay
 <Bfilter>   1e-6*[ 0.0338194   0.1690972   0.3381945   0.3381945   0.1690972   0.0338194]  </B
 <Afilter>        [1.0   -4.7882108   9.1750976  -8.7945960   4.2167989   -0.8090885] </Afilter
-->
```

One set of filter parameters should be uncommented in ConfigRunTime.xml (see section 7.2.7). The "light filtering" parameters are shown uncommented above. The light and heavy parameters are given by Matlab's Butterworth filter design rule (signal processing toolbox required)

```
>> [B, A] = butter(5, 10/30)    %% Light filtering, -3 dB at 10 Hz for 60 Hz sampling
>> [B, A] = butter(5, 1/48)     %% Heavy filtering, -3 dB at 0.625 Hz for 60 Hz sampling
```

The Bfilter and Afilter parameters can be set to any suitable digital filter design.

Filter Initialization Mode:

To suppress startup transients, the filter state can be initialized to the state that would be found after a long period of signals, steady at the current value. This is implement by setting

$$w_{out}(k-1) = ... = w_{out}(k-5) = w_{in}(k-1) = ... = w_{in}(k-5) = w_{in}(k)$$

where $w_{in}(k)$is the current of the corresponding element of ${}^c\mathcal{P}_t^s$.

Initialize the filter state according to jFilterInitializationMode in ConfigRunTime.xml

```
<jFilterInitializationMode> 2 </jFilterInitializationMode>
```

Allowed values:

0: Do not initialize the filter state

1: Initialize the filter state once on the first measurement of the marker pose in program TrackMPT_Marker.

2: Initialize the filter on the first measurement of the marker pose in program TrackMPT_Marker, and re-initialize each time marker tracking is lost and the marker is re-acquired.

Additional Notes on Filtering

- UDP packet

  The values in the UDP packet are listed in section 3.2. Filtered values are inserted into the UDP packet as the x,y,z and qr, qx, qy, qz coordinates.

- Rotations

  Since filtering the individual quaternion components would require 7 rather than 6 values, and would result inconsistent quaternion vectors, the orientation is expressed as Euler angles for filtering, corresponding to $\theta_x, \theta_y, \theta_z$ in Eqn (7). The filtered rotation is computed according to

$$\text{Quaternion}\left({}^{c}_{t}\widehat{R}\right) \quad \text{with} \quad {}^{c}_{t}\widehat{R} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \widehat{R}_z \, \widehat{R}_y \, \widehat{R}_x \tag{8}$$

  where ${}^{c}_{t}\widehat{R}$ is the rotation ${}^{c}_{t}T$ based on the current filtered values of the Euler angles, which give $\widehat{R}_z\,\widehat{R}_y$ and $\widehat{R}_x$. See Eqn (17) in section 7.1 for an explanation of the 180 degree yaw rotation in Eqn (8).

- This filter operates in each MPT process independently.

4.3 TrackMPT_Marker streaming output

`TrackMPT_Marker` has two streaming display mechanisms that permit real-time monitoring of the measured data.

1. Streaming text data to the terminal,

   An example of streaming data is seen in figure 15. Each line includes:

   - Camera frame time (FT:), Status (S:), Marker ID number (M:) and camera frame number (F:). Note: For convenience the frame time is adjusted to show the time since CameraDaemon was started.
   - X, Y, Z, pitch, roll, yaw, the current pose of the MPT marker.

2. Graphing mode, selected from the CameraDaemon command line (see section 4.1.8 for the CameraDaemon option to activate graphing).

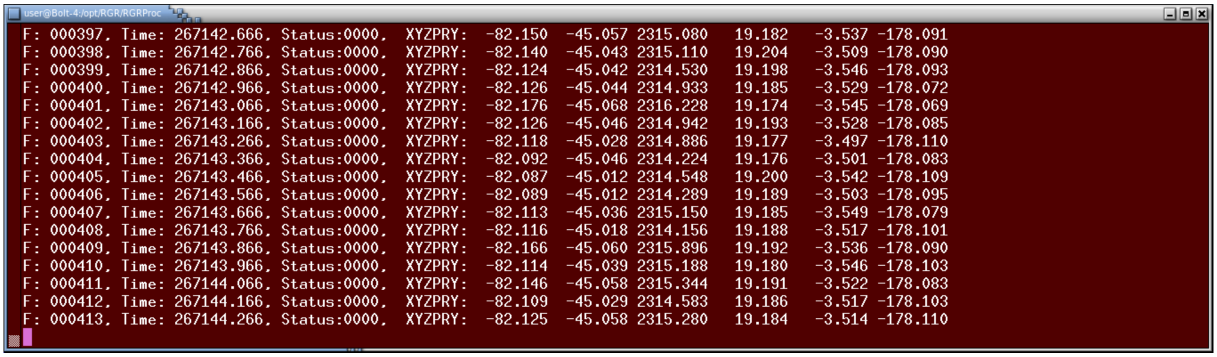
   An example of the real-time plot generated is seen in figure 16.

The position data, marked `XYZPRY:`, is presented as position and orientation in Euler angles.

- The position,

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = {}^{c}P_{\mathring{t}} \tag{9}$$

  where $\begin{bmatrix} X & Y & Z \end{bmatrix}^T$ is the position of the marker [mm] in Camera coordinates,



Example Streamed Data:

```
FT:00017.549 S:00000 M:220 F:02343343 XYZPRY:[+0030.604 +0007.631 +0189.723 +004.7866 +088.6715 -173.1535
FT:00017.560 S:00000 M:220 F:02343344 XYZPRY:[+0030.605 +0007.632 +0189.737 +004.7827 +088.6702 -173.1640
```

Figure 15: Screen shot showing streaming measurements with example streamed data.

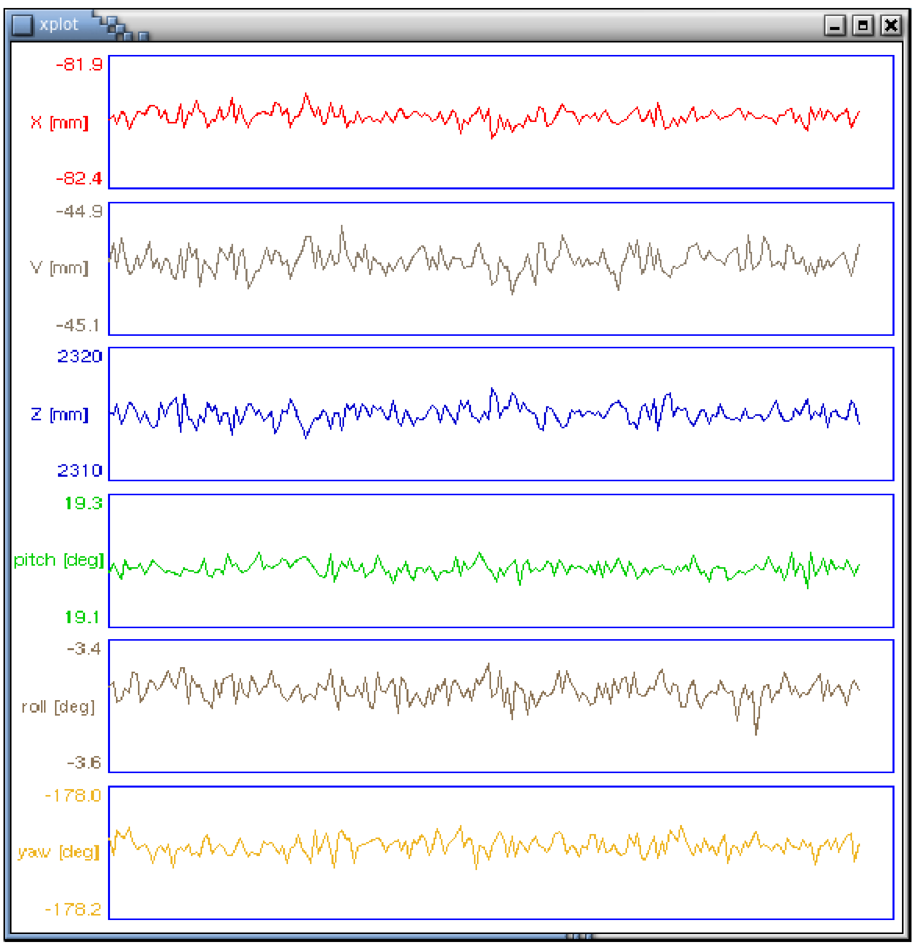


Figure 16: Graphing output of CameraDaemon / `TrackMPT_Marker`.

- Followed by the Euler angles, pitch, roll and yaw (θ_x, θ_z and θ_y). The rotation is given according to:

$$ {}^{r}_{v}R(j) = R_z(j)\, R_y(j)\, R_x(j) \tag{10} $$

where the elementary rotations are given in Eqn (19), below. The Euler angles are calculated in routine `RMatrixRxRyRz2Angles.m`, and ${}^{r}_{v}T(j)$ is defined in Eqn (12), below.

The streaming output can be given in several coordinate frames, described in the next section. Section 7.1 on coordinate frames is recommended reading, before reading the remainder of this section.

4.3.1 Available coordinate frames for streaming output

For the streaming data, the position and Euler angles are given by first calculating the pose of a virtual marker in room coordinates. This pose is given according to:

$$ {}^{r}_{v}T(j) = {}^{r}_{c}T\ {}^{t_0}_{t}T(j)\ {}^{t}_{v}T \tag{11} $$

where

${}^{r}_{v}T(j) \in SE(3)$ is the current measurement of virtual marker pose in room coordinates, this is the pose displayed in both the text and graphical streaming outputs,

${}^{r}_{c}T \in SE(3)$ is the transformation from camera to room coordinates,

${}^{t_0}_{t}T(j) \in SE(3)$ is current measurement of the marker pose, described in section 7.1,

${}^{t}_{v}T \in SE(3)$ is the transformation from the virtual marker pose to the physical marker pose,

and where $SE(3) \subset \mathbb{R}^{4\times 4}$ is the special Euclidean group, it is the set of homogeneous transforms. Homogeneous transform ${}^{r}_{v}T$ is written:

$$ {}^{r}_{v}T(j) = \begin{bmatrix} {}^{r}_{v}R(j) & {}^{r}P_{\mathring{v}}(j) \\ 0\ \ 0\ \ 0 & 1 \end{bmatrix} \tag{12} $$

where ${}^{r}_{v}R(j) \in SO(3) \subset R^{3x3}$ specifies the rotation matrix from virtual marker to room coordinates at time $t(j)$, and ${}^{r}P_{\mathring{v}}(j)$ is the position of the virtual marker in room coordinates.

Note: modifying transforms ${}^{r}_{c}T$ or ${}^{t}_{v}T$ modifies only the streaming output for viewing. The pose data emitted in the UDP packet and logging files is always the pose of the physical marker in camera coordinates.

4.3.2 Setting ${}^r_cT$ and ${}^t_vT$ with **UpdateHomogeneousTransforms**

The measurement coordinate frame and marker coordinate frame can be set by modifying ${}^r_cT$ and ${}^t_vT$ in Eqn (11).

- By setting ${}^r_cT$, the measurement coordinate frame (room coordinates) is established.
- By setting ${}^t_vT$, the pose of the virtual marker relative to the physical marker is established.

Transforms ${}^r_cT$ and ${}^t_vT$ are recorded in the marker context in shared memory (see section 3.1.4) and are modified using the `UpdateHomogeneousTransforms` utility in the bin directory. For example:

```
[user@Bolt-II MPT_TrackingSystem ]$ cd bin
[user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 1

[ ----------------------- ./UpdateHomogeneousTransforms ----------------------- ]
Processing,
  Marker Number        : 112
  Room Coordinate Mode : 2 (Acquire from current measurement)
  Virtual Marker Mode  : 1 (Reset to identity matrix)
Processing completed successfully.
```

The current value of transforms ${}^r_cT$ and ${}^t_vT$ can be viewed using the ShowSharedMemoryState utility. For example, with ${}^r_cT$ and ${}^t_vT$ set as shown

```
[user@Bolt-II bin ]$ ./ShowSharedMemoryState
...
    MarkerData[112].bCaptureRoomCoordinates : FALSE
    MarkerData[112].crT = ...
     [  -0.433468   -0.898817    0.065064     -93.875
        -0.765005    0.405173    0.500603      48.775
        -0.476312    0.167221   -0.863229     772.927
         0.000000    0.000000    0.000000    1.000000]

    MarkerData[112].rcT = ...
     [  -0.433468   -0.765005   -0.476312     364.776
        -0.898817    0.405173    0.167221    -233.388
         0.065064    0.500603   -0.863229     648.903
         0.000000    0.000000    0.000000    1.000000]
```

```
MarkerData[112].bCaptureVirtualMarker : FALSE
MarkerData[112].vtT = ...
 [   1.000000    0.000000    0.000000       0.000
     0.000000    1.000000    0.000000       0.000
     0.000000    0.000000    1.000000       0.000
     0.000000    0.000000    0.000000    1.000000]

MarkerData[112].tvT = ...
 [   1.000000    0.000000    0.000000      -0.000
     0.000000    1.000000    0.000000      -0.000
     0.000000    0.000000    1.000000      -0.000
     0.000000    0.000000    0.000000    1.000000]
```

the *r* or room coordinate frame is expressed in camera coordinates as

$$^{c}P_{\mathring{r}} = \begin{bmatrix} -93.875 \\ 48.775 \\ 772.927 \end{bmatrix} \quad [\text{mm}]$$

and the camera is located in room coordinates at

$$^{r}P_{\mathring{c}} = \begin{bmatrix} 364.776 \\ -233.388 \\ 648.903 \end{bmatrix} \quad [\text{mm}] \; .$$

The UpdateHomogeneousTransforms utility accepts 3 arguments:

```
./UpdateHomogeneousTransforms MarkerIDNumber  RCMode VTMode
```

where

MarkerIDNumber is the marker ID number,

RCMode is the room coordinates mode,

VMMode is the virtual marker mode.

The valid values for RCMode and VTMode are 0, 1, 2 and 3, as described in the next section. In the example invocation above, the marker ID number is 112, `RCMode` is 2 and `VTMode` is 1.

Notes:

Transforms ${}^{r}_{c}T$ and ${}^{t}_{v}T$ are recorded in the marker context in shared memory, which is created the first time a marker is processed by `TrackMPT_Marker`. So a marker must be processed at least once by `TrackMPT_Marker` before `UpdateHomogeneousTransforms` can be used to set ${}^{r}_{c}T$ or ${}^{t}_{v}T$.

Marker ID number 112 is used in the examples that follow. Substitute the actual marker ID number for 112.

4.3.2.1 Modes used with the `UpdateHomogeneousTransforms` utility

The 2^{nd} and 3^{rd} arguments to UpdateHomogeneousTransforms determine how ${}^{r}_{c}T$ and ${}^{t}_{v}T$ are set, respectively. These arguments, `RCMode` and `VTMode`, can take the values of 0, 1, 2 or 3:

0. Do nothing, leave the transformation unchanged. Note that both modes must be set at each invocation.
1. Set the transformation to the identify matrix. Thus, the command

   ```
   [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 1 1
   ```

   will return the streaming data for marker 112 to unmodified camera coordinates.
2. Set the room coordinates to the current (virtual) marker pose, or set the virtual marker pose to the current room coordinates. Thus, the command

   ```
   [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 0
   ```

   will use the current measured pose to set the room coordinate transformation, ${}^{r}_{c}T$, according to:

   $$ {}^{r}_{c}T = \left({}^{t_0}_{t}T\left(j\right)\,{}^{t}_{v}T\right)^{-1}, \tag{13} $$

   and will not change ${}^{t}_{v}T$. This has the effect of setting the room coordinate frame to the current virtual marker location.

   Similarly, the command

   ```
   [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 0 2
   ```

   will use the current measured pose to set the virtual marker transformation, ${}^{t}_{v}T$, according to:

   $$ {}^{t}_{v}T = \left({}^{r}_{c}T\,{}^{t_0}_{t}T\left(j\right)\right)^{-1}, \tag{14} $$

   and will not change ${}^{r}_{c}T$. This has the effect of setting the virtual marker frame to the origin of room coordinates. Each form has the effect of giving

   $$ {}^{r}_{v}T\left(j\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

which gives streaming readings of zero until the marker (or camera) is moved.

A common command form using mode 2 is:

```
[user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 1
```

which sets ${}^{t}_{v}T$ to the identify matrix, and sets room coordinates to the current marker coordinate frame.

Notes:

- Since Eqns (13) and (14) can not be applied simultaneously, command

  ```
  [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 2
  ```

  is disallowed and invokes an error message.

- Commands of the form

  ```
  [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 x
  ```

  or

  ```
  [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 x 2
  ```

  where `x` is one of {0, 1, 3} always execute the non-mode 2 function first. Thus, for example

  ```
  [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 1
  ```

  first sets ${}^{t}_{v}T$ to the identity matrix, then sets ${}^{r}_{c}T$ according to Eqn (13).

3. Load ${}^{r}_{c}T$ or ${}^{t}_{v}T$ from file.

   Command

   ```
   [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 3 0
   ```

   loads ${}^{r}_{c}T$ from file

   ```
   ../RoomCoordinatesHT.txt
   ```

   Command

   ```
   [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 0 3
   ```

   loads ${}^{t}_{v}T$ from file

   ```
   ../VirtualMarkerHT.txt
   ```

   Each file specifies a pose with data of the form:

   ```
   # Any lines starting with a hash are comments and will be ignored
   - 55.630  -39.576  2279.918 (-0.374664 -0.895269 -0.2254967) 0.085259
   ```

   where the first three values are XYZ and the last 4 values specify the rotation as a quaternion, with the vector portion in parentheses and the real component of the quaternion at the end. Note, the position variables are in [mm].

4.3.3 Common forms of the `UpdateHomogeneousTransforms` command

The UpdateHomogeneousTransforms command has 16 variations. Common forms are described here.

4.3.3.1 Set room coordinates from a file To set room coordinates from a file and set virtual marker coordinates to the physical marker use the command

```
[user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 3 1
```

4.3.3.2 Set room coordinates to the current marker position To set room coordinates to the current marker position and set virtual marker coordinates to the physical marker use the command

```
[user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 1
```

4.3.3.3 Setting a virtual marker location With the command

```
[user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 0 2
```

the virtual marker position is set to the current room coordinates. A process to set the virtual marker at known relation to the physical marker would be

1. Position the marker in a first position and set room coordinates to this location with the command

   ```
   [user@Bolt-II bin ]$ ./UpdateHomogeneousTransforms 112 2 1
   ```

4.4 Additional real-time display information

4.4.1 Measurement of Starburst brightness

The mean intensity of the white area of the starburst is passed out as the value `LMIntensity`. This is available as the 4th field of the first landmark record in the B log file, and through the real-time display, as described in section 4.4.3.

4.4.2 Measurement of Starburst focus

A measure of the focus of the MPT marker is computed as:

$$Focus = 10 \frac{\mathrm{std}\,(Pixels)}{\max\,(Pixels) - \min\,(Pixels)} \tag{15}$$

where *Pixels* is a set of pixels near the center of the StarBurst, $\mathrm{std}\,(Pixels)$ is the standard deviation of intensity, $\min(\cdot)$ and $\max(\cdot)$ are the min and max intensity on the set, and *Focus* is a measure of the sharpness of the focus. Eqn (15) operates on the observation that with sharp focus, the distribution of intensities near the center of the Starburst approaches a bi-modal distribution, which maximizes the standard deviation of intensity. Softer focus moves pixels toward the middle value, reducing the relative magnitude of the standard deviation. The focus value is available through the real-time display, as described in section 4.4.3.

4.4.3 Activating real-time display modes with `UpdateHomogeneousTransforms`

The coordinate frame functions of `UpdateHomogeneousTransforms` are described in section 4.3.3. Here, alternative settings are described. These are activated with the UpdateHomogeneousTransforms command and effect how 6 variables are displayed in DisplayMeasurement, which continuously prints measurements to the screen, and in the graphic plot. Graphing is described in section 4.1.8.

Alternate data formats are activated by commands of the form

```
$ ./UpdateHomogeneousTransforms <Marker ID> <Mode Number> <0>
```

4.4.3.1 Example activating display in spherical marker coordinates

For example, when `TrackMPT_Marker` is running on marker 22, the command

```
[user@Bolt-II bin]$ ./UpdateHomogeneousTransforms 22 4 0
```

produces the result

```
[ ----------- ./UpdateHomogeneousTransforms ----------- ]
Processing,
  Marker Number        : 22
  Room Coordinate Mode : 4 (Spherical Marker)
  Virtual Marker Mode  : 0 (Do nothing)
Processing completed successfully.
```

and changes the streaming data display from Camera Cartesian coordinates (standard)

```
FT:00007.686 S:00000 M:022 F:00000104
             XYZPRY:[-0084.394 +0057.752 +2333.262 -014.3255 +052.7041 +156.2580]
FT:00007.835 S:00000 M:022 F:00000105
             XYZPRY:[-0085.011 +0057.052 +2331.898 -014.0422 +053.4041 +156.0490]
```

To Spherical Marker coordinates

```
FT:00004.123 S:00000 M:022 F:00000080
          tSScknot:[+019.7064 +021.3783 +2341.413 +0001.755702 -0043.230 -0001.624764]
FT:00004.269 S:00000 M:022 F:00000081
          tSScknot:[+019.9587 +021.1093 +2341.300 +0001.742157 -0043.964 -0001.648150]
FT:00004.413 S:00000 M:022 F:00000082
          tSScknot:[+020.2156 +020.8812 +2340.652 +0001.730283 -0044.643 -0001.668977]
```

The alternative display modes are listed in table 1. For example, mode 5 can be used to plot and stream the landmark location in pixel coordinates. Mode 6 can be used to observe whether the

Mode Number	Display coordinates	Additional feature
4	Spherical marker coordinates	-
5	Spherical marker coordinates	${}^{s}\omega$ and ${}^{s}\varphi$ replaced with ${}^{p}Y$ and ${}^{p}X$ of the Starburst landmark location
6	Spherical marker coordinates	Append screen message if the Cosine Ambiguity is recovered
7	Spherical marker coordinates	Last value is Starburst intensity
8	Spherical marker coordinates	Last value is Starburst focus

Table 1: Table of alternative display modes.

marker is in a region that will activate Cosine Ambiguity Recovery. Mode 7 can be used to adjust the lighting intensity, and mode 8 can be used to adjust focus (see sections 4.4.1 and 4.4.2).

The alternative display modes are listed in table 1. For example, mode 5 can be used to plot and stream the landmark location in pixel coordinates. Mode 6 can be used to observe whether the marker is in a region that will activate Cosine Ambiguity Recovery. Mode 7 can be used to adjust the lighting intensity, and mode 8 can be used to adjust focus (see sections 4.4.1 and 4.4.2).

4.4.4 Plotted data statistics

When graphing is activated, the addition of the -G switch to `CameraDaemon`

```
[user@Bolt-II bin]$ CameraDaemonFW -gG
```

Will cause CameraDaemon to report statistics on the streaming data values each time the graph is refreshed. Example data is illustrated below. The statistics correspond to the graphed data (cf. figure 15). The data labels correspond to the streaming data mode selected.

```
Graph Statistics, Marker: 0, nData: 41, FrameNumber:   664
                          Mean,     Std. Deviation,   Minimum,      Maximum,   Mean to Extremum
            Az [deg]     16.943587      2.213263     12.140349     20.045496      4.803238
            El [deg]     23.320455      1.453958     21.013203     26.083660      2.763205
             sZ [mm]   2343.953351      1.650452   2341.485840   2346.856689      2.903338
         pitch [deg]      1.863844      0.076637      1.738004      1.997626      0.133782
          roll [deg]    -35.816472      5.726037    -44.223183    -24.039875     11.776597
            SB Focus      1.622146      0.131029      1.385794      1.969982      0.347836
```

4.5 User editable parameter files

One file contains user-editable configuration data:

```
ConfigRunTime.xml
```

This file is described in section 7.2.

4.6 Logging

- The MPT logging system produces 2 files:

  ```
  DRTLog_M<Marker ID Number>_<Creation Date and Time>A.log
  DRTLog_M<Marker ID Number>_<Creation Date and Time>B.log
  ```

  The A log file records measurement data. The B log file records diagnostic/engineering data.

- These files contain text information, so they can be opened in a text editor and examined.

- Text data is stripped out with the UNIX bash script ReduceDRTLogFile which is run on the log file

  ```
  [user@Bolt-II ~]$ ReduceDRTLogFile DRTLog_M023_2010.02.06_23.57.48A.log
  ```

  and produces a data file, such as

  ```
  DRTLog_M023_2010.02.06_23.57.48A.log.dat
  ```

- The log.dat file can be loaded into Matlab, and analyzed directly or with a plotting or a planarity analysis program

```
>> load DRTLog_M023_2010.02.06_23.57.48A.log.dat
>> PlotDRTResults
>> EvaluatePlanarity
```

4.6.1 Fields of the A logging file

The DRTLog_...A.log file contains the information transmitted in a UDP packet. The fields are

- Engineering Data:
  - Logging message time (UNIX time when `program TrackMPT_Marker` called logging)
  - UDP Packet Version
  - Status
  - Frame Number
  - Marker ID Number
- Pose Data (not through estimator)
  - X, Y, Filtered Z (in milli-meters) (this is the only place in the field reflecting the filtered Z data)
  - Quaternion: q_r , q_x , q_y , q_z
- Timing Information
  - Frame Time
  - Count of interrupt events
  - Interrupt time

An example line from an 'A' logging file is:

```
LT:15:16:05.270 V:03 S:00000 M:022 F:00000052
XYZ:[-0049.332 +0079.464 +2344.014]
Q:[+0.07197 -0.22911 +0.94558 +0.21956]
FT:0000000001.232 IS:00 IT:0000000000.000
tSScknot:[+014.7708 +024.7561 +2346.313 +001.9408 -030.1967 -001.2054]
```

This was broken into multiple lines for readability from a single log file line.

4.6.2 Fields of the B logging file

The DRTLog_...B.log file contains engineering data. The fields are

- Logging message time (UNIX time when `program TrackMPT_Marker` called logging)
- Status
- Frame Number
- Marker ID Number
- Number of landmarks located with pHinting (nh) and full search (nf)
- pHint location
- ${}^{c}\mathcal{P}_{\mathring{t}} \in \mathbb{R}^6$ (a 6-vector, distance in meters) (no filtering or estimation)
- ${}^{t}\mathcal{S}_{\mathring{c}} \in \mathbb{R}^6$ (a 6-vector, distance in meters) (no filtering or estimation)
- $\widehat{{}^{s}Z_{\mathring{c}}} \in \mathbb{R}^1$ The estimated value of range.
- Additional diagnostic/engineering data

The 'B' logging file has 48 data fields and 17 labels. Logging of the B logging data to disk is controlled by `ConfigRunTime.xml` parameter `bEnableLogB_LoggingMessages` (see table 3).

4.6.2.1 Time tags in the B log file During processing of each image in TrackMPT_Marker four time tags are recorded:

1. FrameTime: is provided by the drive camera. For the AVT Stingray F033B firewire camera, FrameTime corresponds closely (within microseconds) to the end of the exposure.
2. ImageAcquired: this time tag is recorded when the image becomes available to CameraDaemon.
3. ImageGrabbed: this time tag is recorded when the image is received by TrackMPT_Marker, and processing begins
4. UDPPacketSent: this time tag is recoreded after the return from the function which calls linux

   ```
   send()
   ```

   to send the UDP packet. (Note: UDPPacktSent time is recorded upon return from the callor of `send()`, it is possible that there is additional linux buffering before the packet hits the wire.)

Time tags are recorded in the B log file in this way:

FrameTime: Is given as a time in seconds since 12:00AM, January 1, 1970 (UNIX time, making the count of seconds a very large number).

The value is reported as <seconds>.<microseconds>

ImageAcquired, ImageGrabbed, UDPPacketSent: These times are given as the difference, relative to the FrameTime. Each is give as 0.<microseconds>.

Example data:

```
FT: 1362447858.302077, DIAT: 0.012764, DIGT: 0.013132, DUDPT: 0.019129
FT: 1362447858.314703, DIAT: 0.012741, DIGT: 0.013090, DUDPT: 0.019268
FT: 1362447858.327328, DIAT: 0.012810, DIGT: 0.013145, DUDPT: 0.019678
FT: 1362447858.339952, DIAT: 0.012705, DIGT: 0.013082, DUDPT: 0.019205

DIAT      is Delta - Image Acquisition Time
DIGT      is Delta - Image Grabbed Time
DUDPT     is Delta - UDP Packet Sent Time
```

In the example data, each image spends ~12.8 mill-seconds for transfer from the camera to the computer, and approximately an additional 7 milli-seconds before the UDP packet is sent. An unfortunate characteristic of the firewire interface is that the data rate is used to regulate the frame rate, so the minimum transfer time is (with no other latency) 1/frame_rate. From the measured data, the additional camera and O/S latencies are about 1 milli-second.

4.6.3 Checking the fill-level of the MPT logging partition

Each time `TrackMPT_Marker` is started, the fraction that the logging partition is full is checked, and compared with value `AllowedLoggingDirectoryLevel` from file `ConfigRunTime.xml` (see section 7.2). If the logging partition is over-full, the user is given the options of purging the logging directory or exiting. User options are:

1. Select purge, which deletes all contents of partition

   ```
   /Metria/Logging
   ```

   In this case, all contents of the logging partition are deleted.

2. Exit `TrackMPT_Maker` and selectively delete files from the logging partition.

3. Exit `TrackMPT_Maker` and adjust parameter `AllowedLoggingDirectoryLevel` in file `ConfigRunTime.xml`.

4.7 MPT Lighting system

The MPT lighting system includes power electronics and an LED.

- Power is provided through a BNC connector on the back of the MPT Camera and Lighting Unit. The supply voltage should lie on the range:

$$XX \leq V_s \leq XX \quad \text{[volts]}$$

with shell as ground and pin as V_s.

4.8 MPT marker ID numbers

4.8.1 MPT marker ID number, and Marker series number

For accurate tracking, each moiré phase tracking marker must be associated with its specific calibration information. Calibration files are stored in directory

```
/Metria/Software/MPT_TrackingSystem/ParamFiles
```

The MPT marker calibrations are stored by two numbers:

- Marker Series Number
- Physical Marker ID Number

4.8.2 Marker series number

The marker series number to use must be specified at the time `TrackMPT_Marker` is launched. It is specified either on the command line, or in file `ConfigRunTime.xml`.

When a marker model is sought, function `LoadMarkerModel()` examines the collection of models in the marker series, starting with the first listed MarkerSeriesNumber and continuing until the marker model is located, or all MarkerSeriesNumbers have been examined. The Marker ID number is an 8-bit code, so up to 256 markers can be included within each marker series.

Specifying the marker series numbers in file ConfigRunTime.xml. Fields

```
<MarkerSeriesNumbers>    1001, 1015, 1016 </MarkerSeriesNumbers>
```

specifies the marker series numbers (see section 7.2). Sequare brackets are permitted, so the MarkerSeriesNumbers can be given as:

```
<MarkerSeriesNumbers>    [1001, 1015, 1016] </MarkerSeriesNumbers>
```

The maximum number of MarkerSeriesNumbers is equal to the maximum number Markers that can be tracked. Any MarkerSeriesNumbers past the maximum will be ignored.

Specifying the marker series on the command line with the -S switch. The primary marker series number can be specified using the -S switch when `TrackMPT_Marker` is launched. For example, the line

```
[user@Bolt-II bin ]$ ./TrackMPT_Marker -S 1015
```

specifies that marker series 1015 is to be used as the primary marker series number, over-ridding the value given in the configuration file.

4.8.3 Marker ID number

Each moiré phase tracking marker has a unique 8-bit ID number encoded in eight regions on the marker. This permits 256 unique marker ID numbers, on the range 0 ... 255. Marker ID number 256 is reserved for a generic marker model with each marker series.

Specifying the marker ID number in file ConfigRunTime.xml. Field

```
<PhysicalMarkerIDNumber>       128 </PhysicalMarkerIDNumber>
```

specifies the marker ID number of the marker to track (see section 7.2).

Specifying the marker series on the command line with the -T switch. The marker ID number can be specified using the -T switch when `TrackMPT_Marker` is launched. For example, the line

```
[user@Bolt-II bin ]$ ./TrackMPT_Marker -T 115
```

specifies that marker 115 is to be used , over-ridding the value given in the configuration file.

Automatic marker ID number detection. Additionally, the marker ID number can be automatically detected for one marker in the images, see section 3.1.8. Using this technique, `TrackMPT_Marker` can be initialized with any valid marker ID number, such as 256.

4.8.4 Reading the MPT Marker ID number

The Marker ID Number is read from each marker in each image, providing unique identification and the ability to unambiguously track multiple markers. The Marker ID Number is encoded in black and clear/white triangular marks at the perimeter of the generation VII MPT marker. Place the marker in the zero roll position by finding the one Starburst spoke that is aligned with a circular landmark (see figure 17). The bits are then read out starting at the 11:30 position (most significant bit) and proceeding counter-clockwise. That is, 9:30, 8:30, 6:30, 5:30, 3:30, 2:30, 12:30 (least significant bit). Black triangles correspond to the binary value 0 and white triangles correspond to the binary value 1.

For example, the Marker ID Number in figure 17 is read:

0 0 0 1 1 0 1 0

This is the binary code for the decimal value 26, i.e.. Marker ID 26.

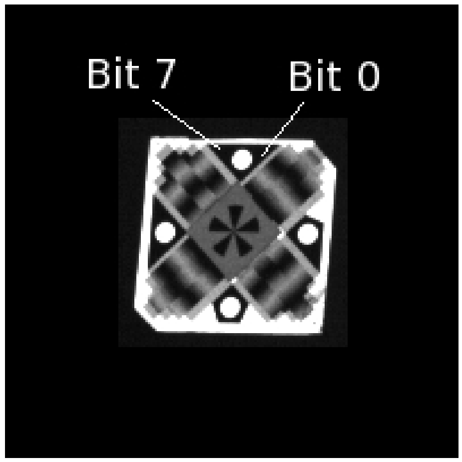


Figure 17: An MPT image with marker, showing the bar code for Marker ID 26.

4.9 Additional utility commands

There are several additional commands available in an MPT system installation.

4.9.1 ShowSharedMemoryState

`ShowSharedMemoryState` is an MPT utility that attaches to the shared memory of a currently running set of `CameraDaemonFW / TrackMPT_Marker` processes and displays shared memory state data. Example data is illustrated below. The shared memory state includes information about the ring buffer described in section 3.1.2 and the marker context described in section 3.1.4.

```
[user@Bolt-II bin ]$ ./ShowSharedMemoryState
ShowSharedMemoryState:  pSharedMemory=7fdcba326000,
                        AttachTime: 0,
                        sizeof(SharedMemoryRecord_t): 9089600
Shared Memory Content :
 bNotify      : 0
 bSaveRing    : 0
 bDoSaving    : 0
 bStop        : 0
 bSaveCropped : 0
```

```
nGrabs        : 13420
&PCA_EstimatorLength: 7fdcba326000, 7fdcbab5a088
PCA_EstimatorLength: 400
Image Ring
 Frame Ring[0].FrameNumber: 00023270, tv_sec : 00241858, tv_nsec : 199458779
 Frame Ring[1].FrameNumber: 00023272, tv_sec : 00241858, tv_nsec : 260452223
 Frame Ring[2].FrameNumber: 00023274, tv_sec : 00241858, tv_nsec : 321441865
 Frame Ring[3].FrameNumber: 00023262, tv_sec : 00241857, tv_nsec : 955495552
 Frame Ring[4].FrameNumber: 00023264, tv_sec : 00241858, tv_nsec : 016484187
 Frame Ring[5].FrameNumber: 00023266, tv_sec : 00241858, tv_nsec : 077475693
 Frame Ring[6].FrameNumber: 00023268, tv_sec : 00241858, tv_nsec : 138468205
 pSharedMemory->MarkerLookup[23], 0, MarkerData[0].MarkerIDNumber: 23
   bGrabbed[0] : TRUE
   bGrabbed[1] : TRUE
   bGrabbed[2] : TRUE
   bGrabbed[3] : TRUE
   bGrabbed[4] : TRUE
   bGrabbed[5] : TRUE
   bGrabbed[6] : TRUE
   MarkerData[23] FrameNumber[0]: 123, MarkerLocation[0]: 1154, 0149 (Col, Row)
   MarkerData[23] FrameNumber[1]: 124, MarkerLocation[1]: 1164, 0159 (Col, Row)
   MarkerData[23].EstimatorData.nSamples: 400
   MarkerData[23].EstimatorData.OuterProdComposite:                (PoseComposite)
        39832.97   36677.59  -1574.62 -26940.00 -224464.93  42244.80  -3991.63
        36677.59   33772.18  -1449.88 -24805.94 -206683.92  38898.38  -3675.44
        -1574.62   -1449.88     62.24   1064.95    8873.23  -1669.96    157.79
       -26940.00  -24805.94   1064.95  18220.17  151811.07 -28571.18   2699.64
      -224464.93 -206683.92   8873.23 151811.07 1264894.67-238056.03  22493.50
        42244.80   38898.38  -1669.96 -28571.18 -238056.03  44802.68  -4233.32
  MarkerData[23].bCaptureRoomCoordinates : FALSE
   MarkerData[23].crT = ...
    [   1.000000    0.000000    0.000000      -0.000
        0.000000    1.000000    0.000000      -0.000
        0.000000    0.000000    1.000000      -0.000
        0.000000    0.000000    0.000000    1.000000]
   MarkerData[23].rcT = ...
    [   1.000000    0.000000    0.000000       0.000
        0.000000    1.000000    0.000000       0.000
        0.000000    0.000000    1.000000       0.000
```

```
          0.000000    0.000000    0.000000    1.000000]
      MarkerData[23].bCaptureVirtualMarker : FALSE
      MarkerData[23].vtT = ...
       [  1.000000    0.000000    0.000000      -0.000
          0.000000    1.000000    0.000000      -0.000
          0.000000    0.000000    1.000000      -0.000
          0.000000    0.000000    0.000000    1.000000]
      MarkerData[23].tvT = ...
       [  1.000000    0.000000    0.000000       0.000
          0.000000    1.000000    0.000000       0.000
          0.000000    0.000000    1.000000       0.000
          0.000000    0.000000    0.000000    1.000000]
   MarkerDataMutex: 1
  *********************  Interpreting Mutex value  ***********************
   Mutex value:   Positive Value: No threads waiting, 0: Threads waiting,
  Negative Value: -(Count of Threads Waiting)
```

4.9.2 ReadInterruptTime

There is a utility available to get the last time value made available by the Interrupt driver.

```
[user@Bolt-II KernelModules]$ ./ReadInterruptTime
Sequence number: 1310; tv_sec = 1277148304; tv_nsec = 876433735; priority = 80;
```

4.9.3 TagDRTLogFile: Log file tagging

As `TrackMPT_Marker` is running it creates log files, as described in section 4.6. The shell script `Utility/TagDRTLogFile` permits tagging a log file, so that the readings corresponding to a specific event can be located.

4.9.3.1 Creating a tag file

For example, these three calls to TagDRTLogFile create 3 entries in the file Tags_DRTLogFile.txt in the session directory where the DRTLog files are created (see section 3.3).

```
[user@Bolt-II MPT_TrackingSystem]$ ./TagDRTLogFile This is a first tag
Tagged frame number 13675 to tag file directory in:
   /Metria/Logging/Session-2010.10.05_15.48.03/Tags_DRTLogFile.txt

[user@Bolt-II MPT_TrackingSystem]$ ./TagDRTLogFile This is a second tag
```

```
Tagged frame number 13720 to tag file directory in:
   /Metria/Logging/Session-2010.10.05_15.48.03/Tags_DRTLogFile.txt

[user@Bolt-II MPT_TrackingSystem]$ ./TagDRTLogFile This is a third tag
Tagged frame number 13760 to tag file directory in:
   /Metria/Logging/Session-2010.10.05_15.48.03/Tags_DRTLogFile.txt
```

The entries in file Tags_DRTLogFile.txt in the session directory will be:

```
[user@Bolt-II Session-2010.10.05_15.48.03]$ m Tags_DRTLogFile.txt
F:13675,  This is a first tag
F:13720,  This is a second tag
F:13760,  This is a third tag
```

4.9.3.2 Breaking out the log files into segments by the tags If the tags mark regions in the data, it may be useful to break out the DRTLog files into segments, based on the tags. To do this

1. cd into the session directory, e.g.,

   ```
   [user@Bolt-II ~]$ cd /Metria/Logging/Session-2010.10.05_15.48.03
   ```

   or

   ```
   [user@Bolt-II ~]$ GoToMostRecentMPTSession
   [user@Bolt-II Session-2010.10.05_15.48.03]$
   ```

2. Launch Matlab, and add the path back to the Diagnostics directory

   ```
   [user@Bolt-II ~]$ Matlab
   >> addpath /Metria/Software/MPT_TrackingSystem/Diagnostics
   ```

3. Run BreakByTags.m

   ```
   >> BreakByTags
   TagLineNumbers =
       24    30    35   132
   ALogFileSegmentName =   DRTLog_M023_2010.10.05_15.48.22A_01.log
   BLogFileSegmentName =   DRTLog_M023_2010.10.05_15.48.22B_01.log
   ALogFileSegmentName =   DRTLog_M023_2010.10.05_15.48.22A_02.log
     ...
   BLogFileSegmentName =   DRTLog_M023_2010.10.05_15.48.22B_04.log
   ```

The directory will contain the indicated log files, each holding a segment of the record.

5 MPT system adjustments

5.1 Adjusting the illumination intensity

The illumination intensity should be adjusted such that the peak intensities for pixels on the MPT marker are in the range 150 - 230. The imager saturates at 255. For best accuracy, it is important that the MPT landmarks (Starburst and circles) not saturate in the image. The factor that determines the illumination intensity is the exposure duration, set when CameraDaemon is launched, as described in section 4.1.

5.1.1 To adjust the illumination intensity for retro-reflective MPT markers:

- In the CameraDaemon preview window type 'i' and/or 'I'

  These keys toggle tools for monitoring the illumination intensity (and are described in section 4.1.7.1).

- Place an MPT marker at the operating distance, oriented to approximately directly face the line of sight to the camera, but with a small tilt angle to avoid marker front face glare.

- Adjust the exposure time and/or the current on the LEDs so that peak intensities in the MPT marker landmarks lie in the range 150 - 230, without saturating.

- Adjustment guidelines:

  - Launch CameraDaemon with various exposure times (-E option), select 'i' and/or 'I' in the preview window.
  - Fine tune the camera exposure time to produce landmark intensities in the range 150 - 230.
  - Record the suitable exposure time, for later use. This will be the standard exposure setting whenever CameraDaemon is launched.

6 Trouble shooting

6.1 If the camera does not start

If CameraDaemon fails to attach to the camera it will emit the following messages (possibly among others):

```
[user@Bolt-II bin ]$ ./CameraDaemonFW
CameraDaemon: No Camera found.
CameraDaemon has been shutdown.
```

In this case,

- Check the power and cable connections to the camera.

6.2 Steps to take if TrackMPT_Marker (the MPT process) halts with errors on screen

- In the event that `TrackMPT_Marker` halts with errors, please do these things to document the halting condition:

  1. Take a screen shot (which will capture any error messages),
  2. Record the shared memory state information.

- To take a screen shot simply press the "Print Screen" key on your keyboard. A dialog box will open requesting a file name for the screen shot.

  An appropriate place to save this image would be in /Metria/Logging/Session_<Session Date&Time>/. Note, the session information is displayed during CameraDaemon startup.

- Another piece of useful information is the current state of shared memory. This can be saved to a file using the following commands.

```
[user@Bolt-II MPT_TrackingSystem]$ cd bin
[user@Bolt-II bin]$ ./ShowSharedMemoryState >
                /Metria/Logging/Session-<Session Date&Time>/SharedMem.txt
```

7 Appendices

7.1 Note on notation

In section 4 and elsewhere, mathematical notation is used to describe rotation matrices, homogeneous transforms and other terms. The notation is described here.

7.1.1 Positions

- All metric quantities are marked with the designation of the coordinate system in which they are measured. For example,

$$ {}^{c}P_{a} $$

  specifies the position of point a in camera, or c, coordinates. A point a is designated by the subscript, and the coordinate frame in which it is expressed is designated by the left superscript.

- The origin of a coordinate frame is indicated with a knot, thus

$$ {}^{c}P_{\mathring{t}} $$

  is the position of the origin of the marker (formerly known as target), or t, coordinates, expressed in camera coordinates.

7.1.2 Points, axes and poses

- Points are written

$$ {}^{c}P_{\mathring{t}} = \begin{bmatrix} {}^{c}X_{\mathring{t}} \\ {}^{c}Y_{\mathring{t}} \\ {}^{c}Z_{\mathring{t}} \end{bmatrix} \in \mathbb{R}^{3} $$

  where ${}^{c}P_{\mathring{t}}$ is the position of $\mathring{t}$ in camera coordinates, and ${}^{c}X_{\mathring{t}}$, ${}^{c}Y_{\mathring{t}}$, and ${}^{c}Z_{\mathring{t}} \in \mathbb{R}^{1}$ are the individual X , Y and Z axis elements. A pose in Cartesian-Camera coordinates is written

$$ {}^{c}\mathcal{P}_{\mathring{t}} = \begin{bmatrix} \theta_{x} \\ \theta_{z} \\ \theta_{y} \\ {}^{c}X_{\mathring{t}} \\ {}^{c}Y_{\mathring{t}} \\ {}^{c}Z_{\mathring{t}} \end{bmatrix} \in \mathbb{R}^{6} \qquad (16) $$

and typed `cPPtknot`, where

$$ {}^{c}P_{\mathring{t}} = \begin{bmatrix} {}^{c}X_{\mathring{t}} \\ {}^{c}Y_{\mathring{t}} \\ {}^{c}Z_{\mathring{t}} \end{bmatrix} $$

is the position of the marker in camera coordinates, and

$$ \begin{bmatrix} \theta_x \\ \theta_z \\ \theta_y \end{bmatrix} $$

are the Euler angles.

7.1.3 Rotations

- The rotation matrix from marker (formerly known as target) to camera coordinates at time $t = t\,(j)$ is specified:

$$ {}^{c}_{t}R(j) = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} R_z\,(j)\; R_y\,(j)\; R_x\,(j) \qquad (17) $$

where ${}^{c}_{t}R(j) \in \mathbb{R}^{3\times3}$ is the Rotation matrix from marker coordinates to camera coordinates. Given the location of a point a on the marker, ${}^{t}P_a$, we could determine the location of the point in camera coordinates as:

$$ {}^{c}P_a = {}^{c}_{t}R\; {}^{t}P_a + {}^{c}P_{\mathring{t}} \qquad (18) $$

where ${}^{c}P_{\mathring{t}}\,(j)$ [mm] is the position of the marker expressed in camera coordinates. In this notation, transformations from one coordinate frame to another are written ${}^{c}_{t}R$ or ${}^{c}_{t}T$, where

the left subscript indicates the frame the transformation is coming from, and

the left superscript indicates the frame the transformation is going to.

and where ${}^{c}_{t}R \in SO\,(3) \in \mathbb{R}^{3\times3}$ is a rotation matrix and ${}^{c}_{t}T \in SE\,(3) \in \mathbb{R}^{4\times4}$ is a homogeneous transformation matrix.

Rotations R_x, R_y and R_z in Eqn (17) are the elementary rotations, given by:

$$ R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_x & -S_x \\ 0 & S_x & C_x \end{bmatrix}, \quad R_y = \begin{bmatrix} C_y & 0 & S_y \\ 0 & 1 & 0 \\ -S_y & 0 & C_y \end{bmatrix}, \quad R_z = \begin{bmatrix} C_z & -S_z & 0 \\ S_z & C_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (19) $$

where C_x and S_x are $\cos(\theta_x)$ and $\sin(\theta_x)$, C_y and S_y are $\cos(\theta_y)$ and $\sin(\theta_y)$, and C_z and S_z are $\cos(\theta_z)$ and $\sin(\theta_z)$, respectively, and where θ_x, θ_y, θ_z [degrees] are the Euler angles of the pose, about the X, Y and Z axes, respectively.

The first rotation matrix in Eqn (17) gives a 180^o y-axis rotation, corresponding to the $+{}^cZ$ axis being the optical axis of the camera, and the $+{}^tZ$ axis being the optical axis of the marker.

- Equation (17) gives the definition of the rotation matrix based on Euler angles for poses expressed in Cartesian-Camera coordinates.
- The homogeneous transform from marker to camera coordinates (and thus the pose of the marker in camera coordinates) is written as:

$$ {}^c_tT(j) = \begin{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} R_z(j)\, R_y(j)\, R_x(j) & {}^cP_{\mathring{t}}(j) \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \tag{20} $$

where ${}^c_tT(j) \in SE(3) \in \mathbb{R}^{4\times4}$ indicates the transformation from camera, or c, coordinates, to marker, or t, coordinates, on the j^{th} sample.

- Note that the definition of Euler angles internal to the MPT system is given by Eqn (17), which results in `pitch=`0^o`, roll=`0^o`, yaw=`0^o when the marker is parallel to the image plane of the camera.

7.1.4 For streaming data

For streaming data (section 4.3), ${}^{t0}_tR$ and ${}^{t0}_tT$ are defined.

$$ {}^{t0}_tR(j) = R_z(j)\, R_y(j)\, R_x(j) = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}^{-1} {}^c_tR(j) \tag{21} $$

$$ {}^{t0}_tT(j) = \begin{bmatrix} {}^{t0}_tR(j) & {}^cP_{\mathring{t}}(j) \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \tag{22} $$

7.2 Configuration file ConfigRunTime.xml

Configuration of the MPT system is set in file ConfigRunTime.xml,

```
/home/user/.mpt/ConfigRunTime.xml
```

`ConfigRunTime.xml` can be edited with any text editor, such as gedit, vi or emacs. The sections of file `ConfigRunTime.xml` are described below.

7.2.1 Basic run-time configuration

Basic run time configuration parameters are listed in table 2. The parameters of greatest interest for the user are `UDPHost`, `UDPPort` and `PhysicalMarkerIDNumber`, which set the destination of the UDP packets with measurements, and the default marker ID number.

Field Name	Example Data	Significance	Allowed Range or Values
Version	1.00	Used by Metria	-
CameraName	AVT-StingrayF033B-xx	Name and serial number of the MPT camera	As given (changed only if the CLU is exchanged).
LensName	UKA9mmf8	Name of the lens type	UKA9mmf8
UDPHost	192.168.1.1	Destination of the UDP packets	Any valid IP address
UDPPort	22222	Port number to which UDP packets are sent	Any valid IP port number
PhysicalMarker IDNumber	192	ID Number of the default marker	0 ... 256
Marker SeriesNumbers	1001, 1015, ...	Marker series numbers to search when loading a marker model	Provided by Metria
jMirror	1	jMirror > 0 indicates that a mirror is used	1 for the CLU-384ib
SharedMemory BaseKey	4100	Used by Metria	-
GrabThreshold	100	Number of valid MPT data reads to activate the save-ring mechanism (see section 3.1.3.1)	1 .. $\left(2^{31}-1\right)$

Table 2: Significance of `ConfigRunTime.xml` entries. Significance of parameters of the basic run-time configuration.

7.2.2 Overall MPT system parameters

Overall MPT system parameters are listed in table 3.

Field Name	Example Data	Significance	Allowed Range or Values
AllowedLogging DirectoryLevel	0.850	Maxim fill-fraction allowed for the logging partition. See section 4.6.	0.0 ... 0.99
bEnableLogB Logging Messages	true	Activate recording of the B log file (see section 4.6)	true / false
bEnableAuto MarkerDetect	true	Activate automatic detection of the marker ID number (see section 3.1.8)	true / false
nSuccessful FindsFor AutoDetect	3	Number of times a marker must be seen for automatic detection	1 .. $\left(2^{31}-1\right)$

Table 3: Significance of `ConfigRunTime.xml` entries (continued).

7.2.3 Camera daemon parameters

Field Name	Example Data	Significance	Allowed Values
Exposure	400	Camera exposure in micro-seconds	1 - 1000000
FrameRate	82.0	Camera frame rate	1 .. 84.9
bShowPreviewWindow	true	Open the preview window on startup	true / false
bShowGraphingWindow	false	Open the graphing window on startup	true / false
ImageSaveCount	200	Number of images to save when the save image mechanism is triggered. (see sections 4.1.7.1)	Limited by system RAM.
ImageSaveRate	2.0	Frame rate at which to save images (see section 4.1.5)	0 ... FrameRate
EKG_RedrawInterval	0.1	Time interval to update data in the streaming plot graphic [seconds]. (see section 4.1.8)	Useful range is lower-bounded by the refresh rate. No upper limit.
EKG_XAxisPeriod	20	Period of the X axis of the streaming plot graphic [seconds].	Period is limited by the sample rate and EKG buffer size of 1200 samples.
InitialDisplayMode	1	Initial display mode for displayed and graphed data.	0-8 see section 4.4.3 and table 1.

Table 4: Significance of `ConfigRunTime.xml` entries (continued).

7.2.4 Timing and filter parameters

Field Name	Example Data	Significance	Allowed Values
irqDelay_uS	8	Delay between rising edge of the external timing signal to Tirq_registered	0 .. 999,999
frameDelay_uS	0	Delay from end of exposure to time-tagging of image	0 .. 999,999
bEnablePCA_Element	[true ... false]	6 Vector controlling whether a given element of vector ${}^t\mathcal{S}_{\mathring{c}}$ is included in PCA Estimation	6-vector of {true/false} Values must be logical (Boolean) type.
jFilterInitializationMode	2	Controls when the filter state is initialized (see section 4.2.2.1).	0, 1, 2
bRunFilter	[true ... true]	Controls which elements in ${}^c\mathcal{P}_{\mathring{t}}$ are filtered using `Bfilter` and `Afilter` (see section 4.2.2.1).	true / false
Bfilter	[1 ... 0]	B polynomial of Butterworth filter on ${}^cZ_{\mathring{t}}$	Given by filter design
Afilter	[1 ... 0]	A polynomial of Butterworth filter on ${}^cZ_{\mathring{t}}$	Given by filter design

Table 5: Significance of `ConfigRunTime.xml` entries (continued).

7.2.5 Cosine ambiguity recovery control parameters

Parameters controlling Cosine Ambiguity Recovery, see section 3.1.6. These parameters are generally not user adjustable.

Field Name	Example Data	Significance	Allowed Values
bEnableCosineAmbiguityRecovery	false	True enables Cosine Ambiguity Recovery (see section 3.1.6).	true / false
NearTDCThreshold	10.0	CAR parameter	0 - 90
PoseHat1RejectCycles	0.3	CAR parameter	0 - 1
nMinGoodFramesToActivate	5	CAR parameter	0 and up
nBadFramesToDeactivate	5	CAR parameter	0 and up
nMaxFrameNumberGap	10	CAR parameter	0 and up

Table 6: Significance of `ConfigRunTime.xml` entries (continued). Parameters controlling Cosine Ambiguity Recovery.

7.2.6 Find starburst parameters

The starburst landmark is the robust landmark at the center of the MPT marker. Its detection is controlled by these parameters. These parameters are generally not user adjustable.

Field Name	Example Data	Significance	Allowed Values
StarburstRadius	5.5	Radius used to detect Starbursts	5.5 - 9.5 [pixels]
StarburstStepFactor	0.3	Starburst parameter	0.3
StarburstMaxTilt	60	Starburst parameter	0-60 [degrees]
StarburstMinGapPixels	1.5	Starburst parameter	1.5
StarburstHintClickRadius	10	Starburst parameter	0-10 [pixels]
StarburstPreSearchIntensityThreshold	20	Starburst parameter	0 - 255 [intensity]
StarburstPreSearchCountThreshold	6	Starburst parameter	6
StarburstPreSearchPaddingCount	6	Starburst parameter	6

Table 7: Significance of `ConfigRunTime.xml` entries (continued). Parameters controlling Starburst detection.

7.2.7 Comments in .xml files

Comments in .xml files have the format

```
<!--  A Comment -->
So material of the form:

  <!--
   <Bfilter>            [1 0 0 0 0 0 ]  </Bfilter>
   <Afilter>            [1 0 0 0 0 0 ] </Afilter>
   -->

is commented out, and material without the <!--   --> bracket is
included.
```

7.3 Calibration data

7.3.1 Measured latencies

- End of exposure to receipt-of-image time (`Tframe_arrival` in section 3.1.9) for AVT Prosilica GC-650 camera

  10939 μs

- Rising edge of the external timing signal to `Tirq_registered` time

  8 μs

7.4 Setup checklist

This checklist is for confirming the correct setup and configuration of MPT. Check for correct:

1. Configuration (mirror status, IP address, etc.)
2. Camera model
3. Marker models
4. Check voltage at the CLU