# NVIDIA JETSON TX1

TDG-08214-001_v01 | September 2016

## Thermal Design Guide

# DOCUMENT CHANGE HISTORY

TDG-08214-001_v01

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# Chapter 1. INTRODUCTION

## 1.1 OVERVIEW

This design guide is the thermal design guide (TDG) for the NVIDIA® Jetson™ TX1 product (699-82180-1000-100).

The purpose of this design guide is to provide the system-level thermal, mechanical and qualification requirements for the Jetson TX1.

Refer to the Jetson TX1 Module data sheet for detailed drawing and module dimensions.

## 1.2 CUSTOMER REQUIREMENTS

The requirements are as follows:

- Customers are responsible for reading and understanding this entire thermal design guide.
- Customers are responsible for implementing a thermal solution that maintains the NVIDIA® Tegra® X1 and TTP temperatures below the specified temperatures in Table 2-1 under the maximum thermal load and system conditions for their use case.
- Customers are responsible for designing a system that delivers sufficient power to the Jetson TX1 to sustain the maximum thermal load for their use case.
- Customers are responsible for qualification of the Jetson TX1 in their system and are responsible for any issues related to failure to qualify the product properly.
- The TTP is not designed to be removed by the customer, as the thermal interface material cannot be reused. The screws holding the TTP together are marked with tamper evident ink. Removal of the TTP is done solely at the customer's risk.

# 1.3 DEFINITIONS

This section describes terminology that will be referenced throughout this thermal design guide.

## 1.3.1 Total Module Power

The total module power (TMP) represents the average board power dissipation while the system is running the target workload under the worst-case conditions in steady state. System designs must be capable of providing sufficient cooling for the Jetson TX1 when operating at the TMP level.

### 1.3.1.1 TMP Conditions

TMP conditions for this design are defined under the following operating conditions:

- Worst-case Tegra temperature conditions
- Maximum power level for the product configuration
  - The TMP power level is based on the target workload
- Steady state average power

## 1.3.2 Thermal Transfer Plate

The Jetson TX1 module is provided with a thermal transfer plate (TTP) to simplify integration with a system-level thermal solution. The Jetson TX1 is shown in Figure 1-1 (topside view) and Figure 1-2 (backside view).

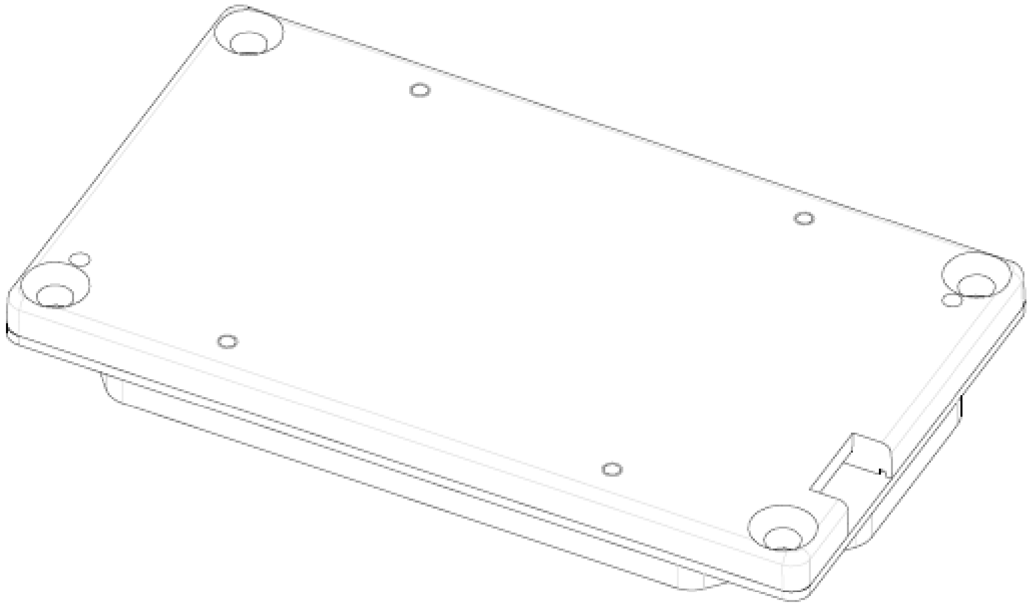


Figure 1-1. Jetson TX1 – Topside View

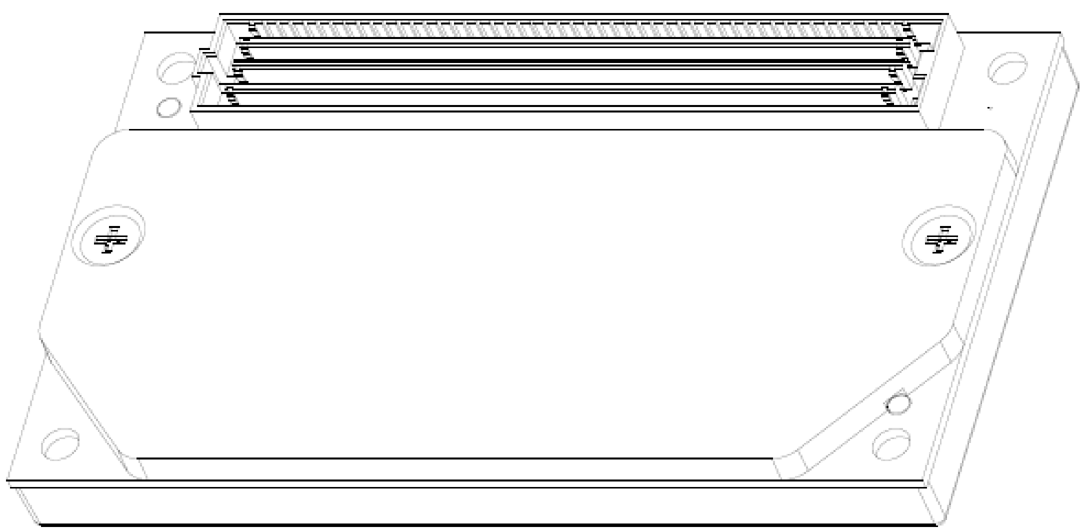


Figure 1-2. Jetson TX1 Backside View

The thermal solution of the customer's system design should attach to the top surface of the TTP. Mounting holes are provided on the top surface of the TTP to enable attachment of the customer's thermal solution. More details are provided in Section 3.2 "Mechanical Information."

An exploded view of the Jetson TX1 assembly is shown in Figure 1-3. The PCB is completely covered by the TTP (thermal transfer plate), with the exception of the WiFi antenna connectors. The TTP design mechanically isolates the Jetson TX1 board and components from external mechanical forces, standardizes the thermal and mechanical interface, and allows for modular system design.

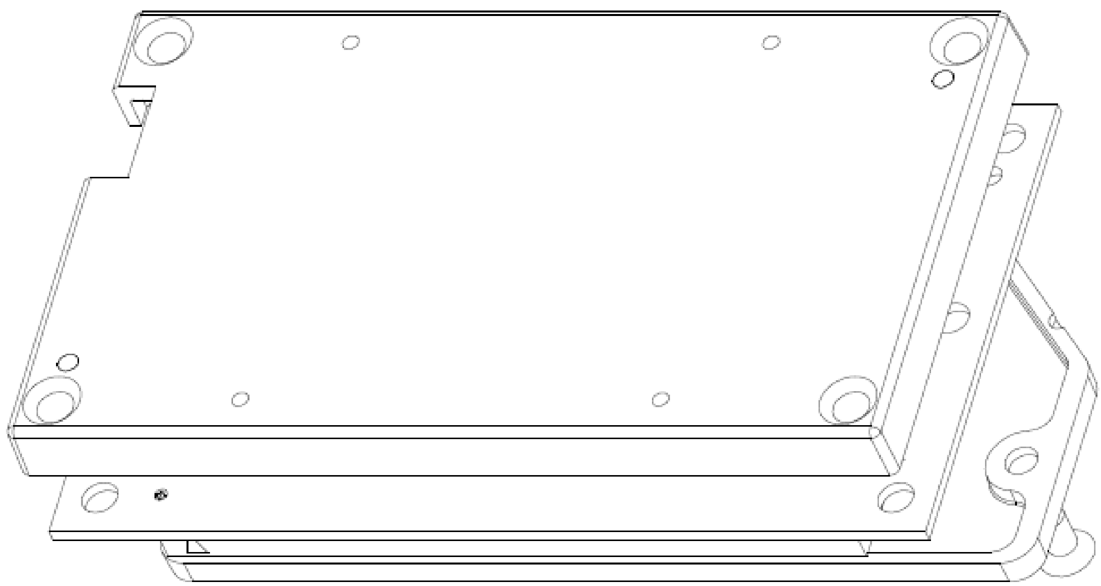


Figure 1-3. Jetson TX1 Design – Exploded View

## 1.3.3 Tegra X1 Temperature

The Tegra X1 junction temperature ($T_j$ ) represents the Tegra X1 die temperature read from any of the internal temperature sensors. The on-die thermal sensors are used for high-temperature $T_j$ management and many other temperature-dependent functions. Details regarding the software thermal mechanisms are described in Chapter 4

# Chapter 2. SPECIFICATIONS

## 2.1 THERMAL SPECIFICATIONS

On Tegra X1 there are multiple on-die temperature sensors that are placed close to dominant hotspots for high accuracy measurements of junction temperature. A built-in hardware controller is used to read the sensors and engage thermal protection mechanisms. Chapter 4 contains the details related to these sensors and the associated thermal protection mechanisms. The specifications in Table 2-1 must be followed in order to maintain the performance and reliability of the Jetson TX1 module.

### Table 2-1. Jetson TX1 Thermal Specifications

| Parameter | Value | Units |
| --- | --- | --- |
| Maximum TTP operating temperature[1] | 80 | °C |
| Maximum Tegra X1 operating temperature[2] | T.cpu = 89 | °C |
| | T.gpu = 90.5 | °C |
| Tegra X1 shutdown temperature[3] | T.cpu = 103 | °C |
| | T.gpu = 104 | °C |

**Notes:**

[1] The temperature of the TTP must always be kept under this 80 °C limit in order to maintain the required performance and reliability. The measurement location is provided in Figure 3-2.

[2] The Tegra X1 maximum operating temperature is the temperature below which the product will operate at the specified clock speeds. Software will apply clock speed reductions once this temperature is reached. Note that power fluctuations that induce $T_j$ fluctuations above these thresholds will cause temporary clock reductions. See Section 4.1 for details.

[3] The Tegra X1 will shut down the Jetson TX1 module once any of these software imposed temperature limits are reached in order to maintain the reliability of the Tegra X1. See Section 4.5 for details

# Chapter 3. DESIGN GUIDANCE

This chapter provides design guidance for the Jetson TX1 module in order to meet customer product specifications.

## 3.1 THERMAL INFORMATION

The design goal for system thermal management is to keep the Tegra X1 temperature and TTP temperature below the limits specified in Section 2.1. The TTP temperature limit maintains the component temperatures on Jetson TX1 within their temperature specifications.

### 3.1.1 Jetson TX1 Thermal Performance

The Jetson TX1 module is designed to have a system level thermal solution attached to the TTP to dissipate the TMP thermal load into the ambient environment. This can be represented with a thermal resistance network where thermal resistance is calculated based on the equation:

$$\theta_{12} = \frac{T_1 - T_2}{P}$$

Where:

| | |
|---|---|
| $\theta_{12}$ | The thermal resistance between Point 1 and Point 2 |
| $T_n$ | The temperature at Point $n$ |
| $P$ | The heat load (i.e; dissipated power) transferred between Points 1 and 2 |

A simple example of a thermal resistance network is shown in Figure 3-1, where $\theta_{jp}$ represents the thermal resistance from $T_j$ to the TTP and θpa represents the thermal resistance of the system thermal solution. The thermal resistance of the system thermal solution may include multiple components including, but not limited to, thermal interface material, heat spreaders, and heat sinks.

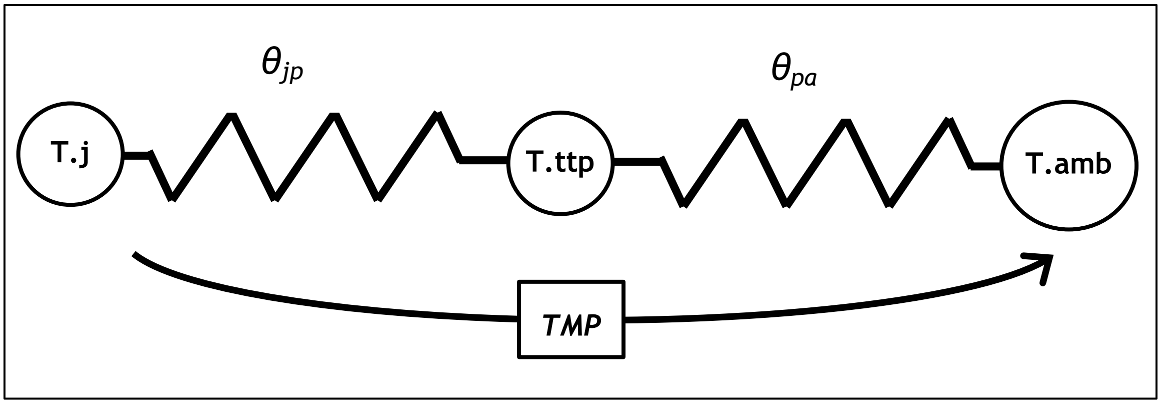



Figure 3-1. Thermal Resistance Network

Jetson TX1 enables a wide variety of applications that may exercise different components on the module. The variation between applications will cause variation in heat loads on the different components on the Jetson TX1 and hotspots in different logical partitions of the Tegra X1. While the TTP design helps to spread the heat and make the thermal performance as consistent as possible, different applications will have different levels of thermal performance. The more evenly the module power is distributed across the Jetson TX1 the higher the thermal performance will be. A few examples of alternately distributed workloads are shown in Table 3-1 for reference.

## Table 3-1. Jetson TX1 Thermal Performance

| | **CPU Only Workload**[1] | **GLBenchmark Manhattan Workload**[2] |
|---|---|---|
| $\theta_{jp}$ | 1.15 °C/W | 0.75 °C/W |

**Note:**

[1]A CPU only workload and is one of the most thermally challenged use cases because the power is concentrated on a small area of the Tegra X1. This is not representative of most use cases.

[2]CPU light, GPU heavy, SOC light, DRAM heavy use case, results in power being widely distributed. It is representative of the thermal performance that is obtained with a more balanced workload.

The thermal resistance of the module ($\theta_{jp}$) and heat sink ($\theta_{pa}$) sum together for the overall thermal resistance from Tegra X1 to ambient. The required heat sink thermal performance can be determined based on the ambient temperature conditions, use case, and TMP level required by the customer. Consider the following example:

$T.amb = 55°C$

$T.cpu = 85°C$ (Targeting $4°C$ T.cpu headroom to account for sensor inaccuracy and possible $T_j$ fluctuations resulting from workload variation)

$$\theta jp = 1 \frac{°C}{W}$$

$P_{TMP} = 10W$

First, check the heat sink thermal performance requirement for the above conditions.

$$\theta_{ja} = \theta_{jp} + \theta_{pa} \rightarrow \theta_{pa} = \theta_{ja} - \theta_{jp} = \frac{85°C - 55°C}{10W} - \theta_{jp} = 3\frac{°C}{W} - 1\frac{°C}{W} = \mathbf{2}\frac{°\boldsymbol{C}}{\boldsymbol{W}}$$

So the heat sink's thermal performance ($\theta_{pa}$) must be better than 2 °C/W. Next, check that the TTP temperature will be below the 80 °C specification.

$$\theta_{pa} = \frac{T_p - T_a}{P} \rightarrow T_p = \theta_{pa} * P - T_a = 2.0\frac{°C}{W} * 10W + 55°C = \mathbf{75°}\boldsymbol{C}$$

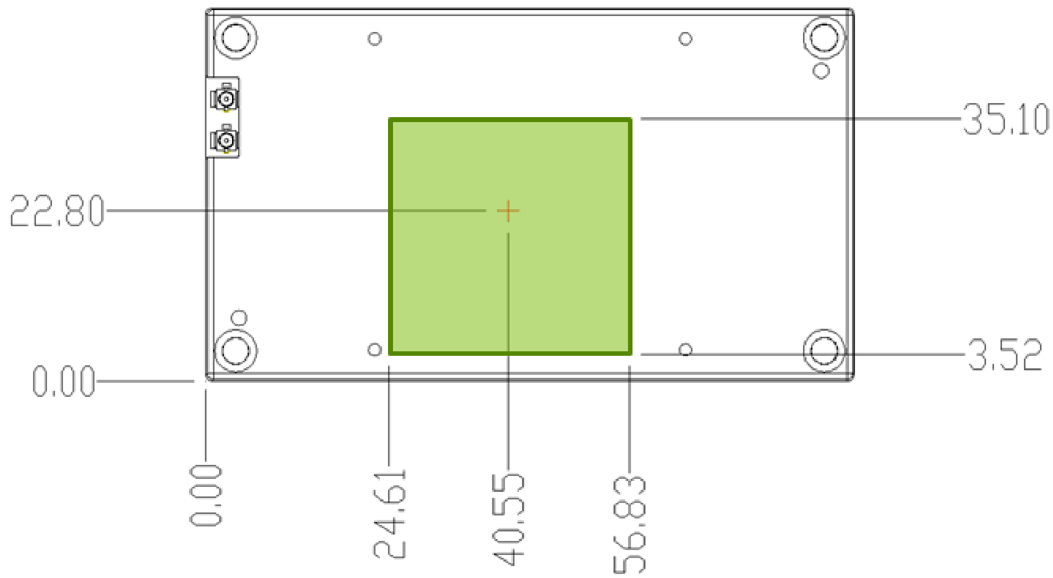
So the 2 °C/W thermal solution is expected to be sufficient to maintain the Tegra X1 and TTP temperature specifications.

### 3.1.2 Jetson TX1 Thermal Design Details

The Jetson TX1 module is designed for integration with a system-level thermal solution which could be a passive heat sink, an active heat sink, a cold plate, a chassis mount, etc. The thermal solution must attach to the top surface of the TTP.

The 32 mm × 32 mm area directly above the Tegra X1, as shown in Figure 3-2, is the key contact area for efficient cooling performance. Full contact with the entire top surface of the TTP is suggested for maximum cooling.

The TTP has a maximum operating temperature specified in Table 2-1. If the Jetson TX1 temperature is kept below this limit, then all other critical components on the PCB will be within their temperature limits as well. The TTP temperature is to be measured during the qualification testing at the location indicated by a red cross (+) in Figure 3-2.




## Figure 3-2. Location of TTP Thermocouple

In the Z-direction, the cold plate thermocouple should be located on the surface of the TTP as shown in Figure 3-3, indicated by Location 2. During thermal qualification, this is the only temperature that needs to be monitored with a thermocouple. The Tegra X1 temperature (Location 1) is monitored via software. Note the following for Figure 3-3:

### Jetson TX1 Contents

- Thermal transfer plate and backside stiffener – The thermal transfer plate has an internal heat spreader plate connected to Tegra X1 in order to reduce the thermal performance variation between workloads.
- PCB with components
- TIM – Henkel GF3500S35. TIM is applied all components necessary to maintain the component temperatures within their specified limits.

### Customer Requirements

The customer is responsible for the following items:

- HS_TIM – The customer is responsible for providing the thermal interface material between the TTP and the thermal solution. For best thermal performance, the TIM should provide low thermal impedance within the mechanical, reliability, and cost constraints of the customer's product.
- Thermal Solution – A thermal solution capable of cooling the appropriate amount of TMP for the target workload.
- Maximum TTP Temperature - To ensure that the maximum Tegra X1 operating temperature is less than the value specified in Table 2-1 (shown as Location 1 in

Figure 3-3), and the maximum TTP temperature must not exceed the value specified in Table 2-1 (shown as Location 2 in Figure 3-3).

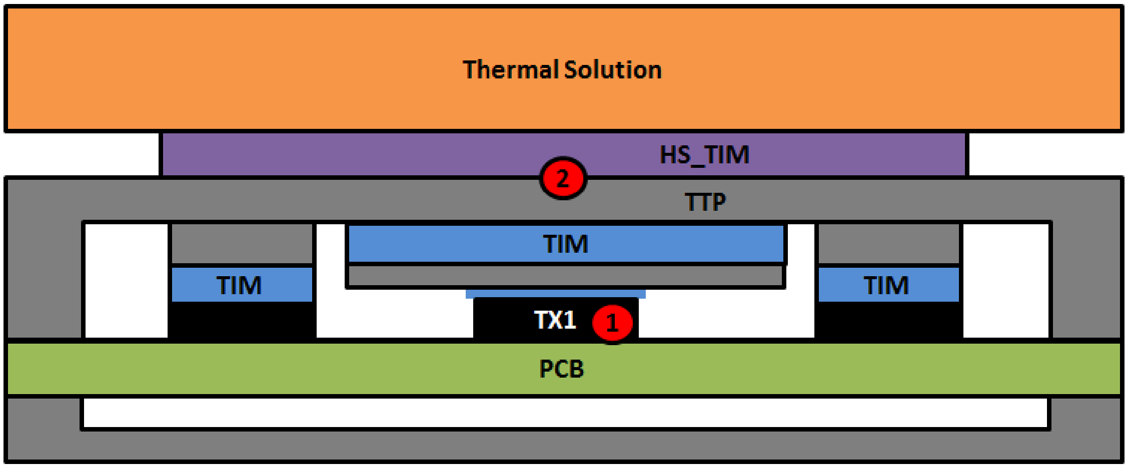



Figure 3-3. Thermal Stack-Up Schematic

## 3.1.3 Customer Thermal Solution

The customer's thermal solution is the mechanical element that interfaces to the NVIDIA TTP and provides cooling. The thermal solution must attach to the top surface of the TTP but a variety of configurations are possible depending on the customer's chassis design. In all cases, however, the following recommendations are applicable:

- Good contact of the thermal solution to the center of the TTP is critical for maximizing the thermal performance of the Jetson TX1. The Tegra X1 is located under the center of the TTP and consumes the majority of the TMP. Thus, good thermal transfer between the thermal solution and the center of the TTP is crucial.
- NVIDIA thermal testing has demonstrated that as long as the cold plate temperature does not exceed the maximum specified temperature, then the rest of the components will be below their operating temperature limits.

## 3.1.4 Temperature Cycling

Long-term reliability of all solder interconnects is negatively impacted by temperature cycling. It is the customer's responsibility to minimize the component's exposure to temperature cycling and to not exceed that which the component is qualified. NVIDIA's graphics and core logic components are qualified to JEDEC standard JESD47.

> **Note:** NVIDIA recommends that customers refer to JESD94.01 (*Application Specific Qualification Using Knowledge Based Test Methodology*) for more information.

# 3.2 MECHANICAL INFORMATION

Refer to the Jetson TX1 module mechanical drawing for the exact module dimensions to determine how to interface the TTP with the system thermal solution and ensure mechanical compatibility.

## 3.2.1 Heat Sink Mounting Guidelines

As noted in the thermal section, the mechanical design of the system must ensure good contact between the thermal solution and the center of the TTP. The TTP is provided with mounting holes to accommodate mounting options for a heat sink. M2 screws should be used for mounting a customer's heat sink. The depth of the M2 threaded hole on the TTP is 3.0 mm maximum as shown in Figure 3-4. Hardware threaded beyond the 3.00 mm depth could lead to permanent damage.

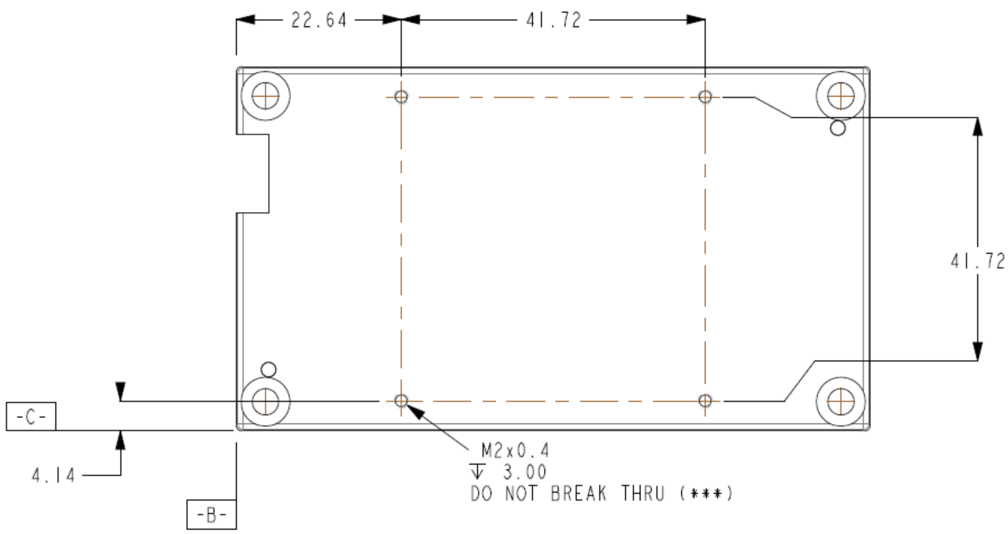



Figure 3-4. Heat Sink Mounting Pattern

The following guidelines should be followed to ensure good mechanical and thermal contact between the chassis thermal solution and the TTP.

- M2X0.4 screws should be used for all mounting hole locations.
- For all mounting screws, a maximum torque of 0.1 N-m is recommended. The tightening sequence shown in Figure 3-5 should be done in two cycles with the last one as maximum torques recommended.
- M2 screw depth requirements – Refer to Figure 3-4.
  - Item 1: The four mounting holes in the TTP area should not exceed a depth of 3.0 mm as measured from the surface of the TTP.
  - Item 2: Follow the torque pattern sequence as shown in Figure 3-5.

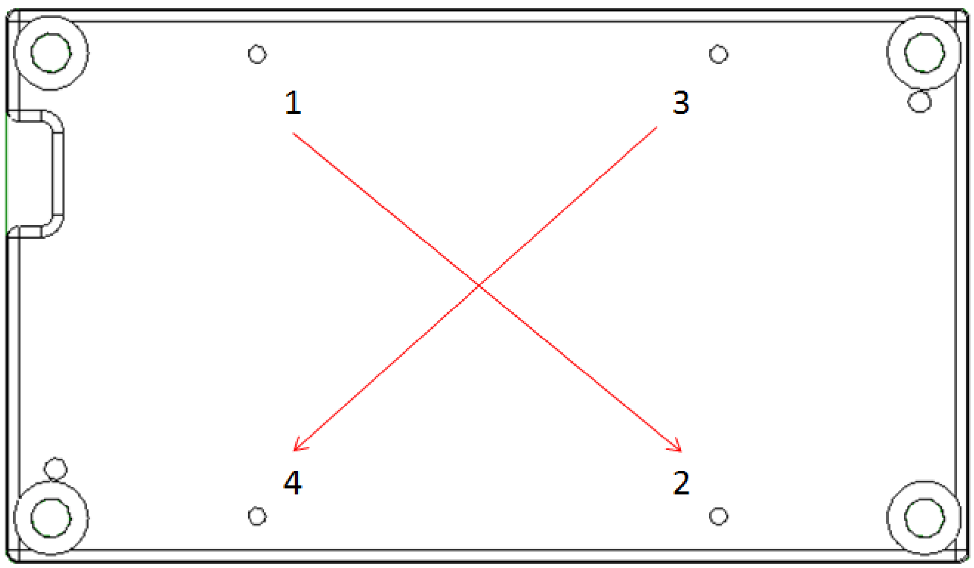



Figure 3-5. Torque Pattern Sequence

### 3.2.2 Assembly Guidelines

The Jetson TX1 and TTP are provided as a complete unit. Orientation of the unit is to be aligned with the board-to-board connector and secured to the baseboard as shown in Figure 3-6. Suggested hardware for mounting is four M3X0.5X7 mm long female-female standoffs.

Here are some suggested assembly guidelines.

1. Assemble the heat sink and fan combination.
2. Install the Jetson TX1 by the carefully aligning the connector.
   a) Each mounting M3 screw should be attached loosely in the sequence shown in Figure 3-5. The tightening sequence should be followed for two cycles. On the last tightening sequence, the screws should be fully torqued.

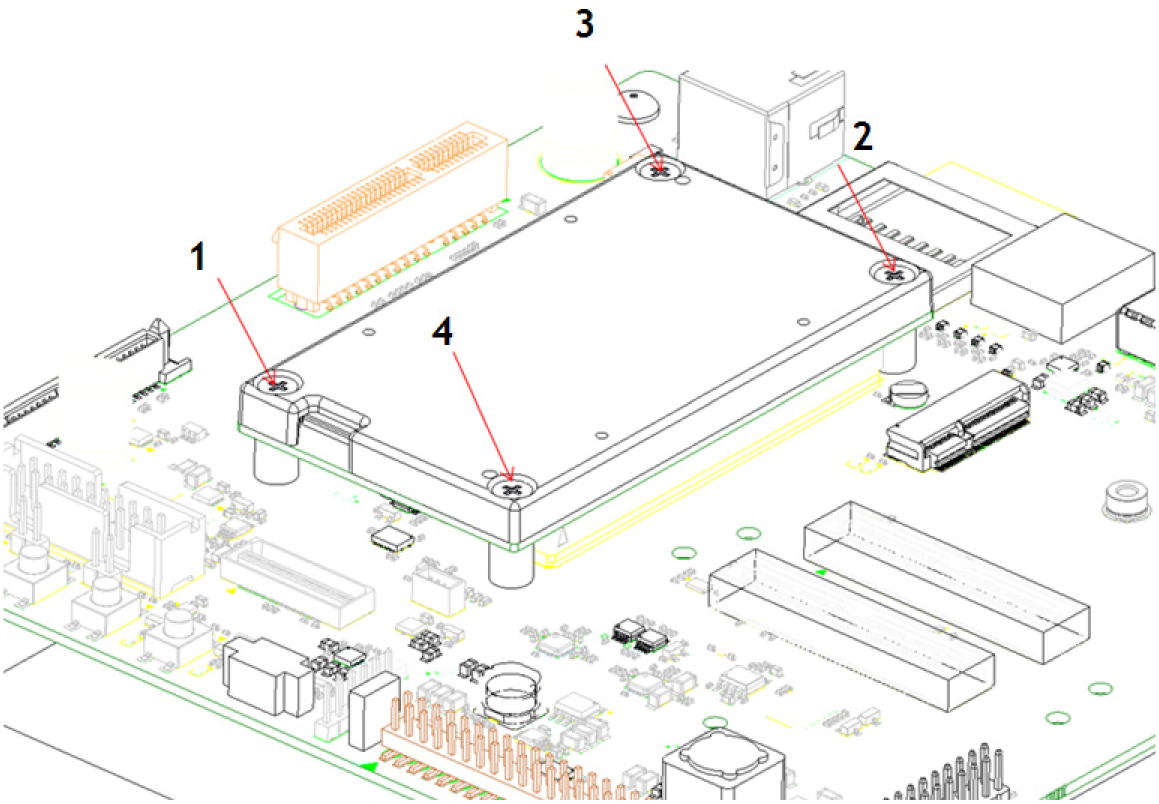



Figure 3-6. Jetson TX1 System Assembly Example

# Chapter 4. THERMAL MANAGEMENT

## 4.1 TEMPERATURE MONITORING

The Tegra junction temperature can be directly read from sysfs nodes, as shown in the following example. Note that the name of each temperature zone is noted in the type node and that the temperature values are reported in units of m °C.

```
# cat /sys/devices/virtual/thermal/thermal_zone1/type
cpu-therm
# cat /sys/devices/virtual/thermal/thermal_zone1/temp
35000
```

## 4.2 FAN CONTROL

The Jetson TX1 can be configured to control a system fan. Pulse width modulation (PWM) output and tachometer input are supported. Jetson TX1 has configurable fan control of step based speed control with hysteresis, as shown in Figure 4-1.

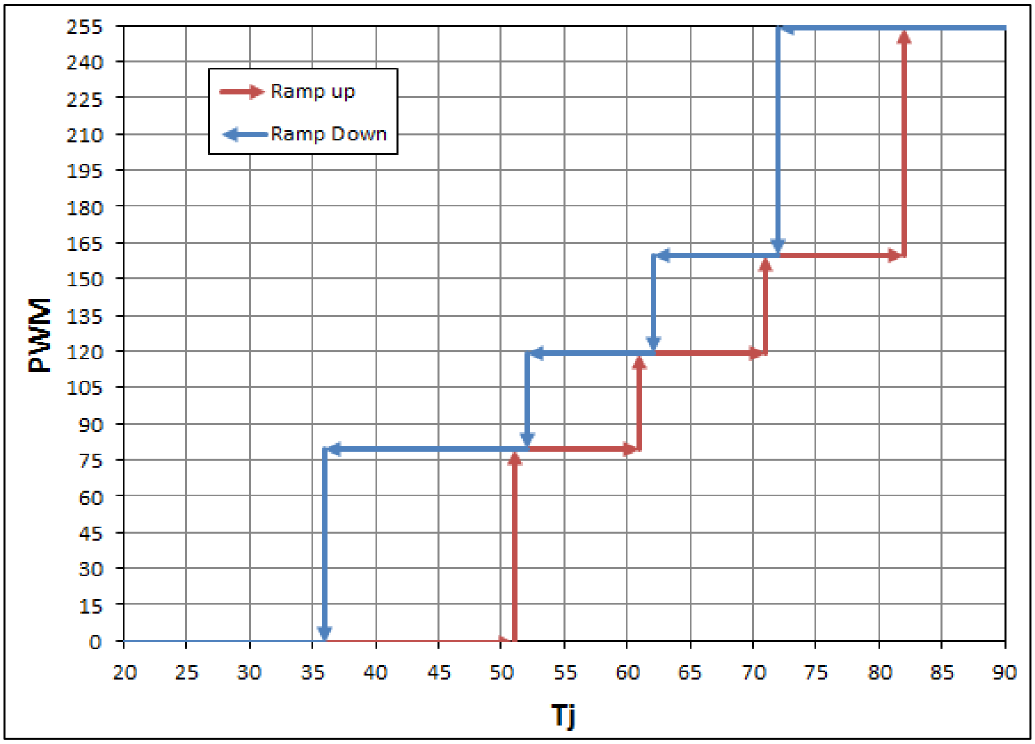



Figure 4-1. Fan Control Algorithm

The default fan curve settings are listed in Table 4-1. Note that PWM is configured on a 2^8 scale, with 255 being equivalent to 100% duty cycle.

Table 4-1. Default Fan Control Parameters

| CPU Temperature (°C) | PWM | Hysteresis[1] (°C) |
|---|---|---|
| 51 | 80 | 15 |
| 61 | 120 | 9 |
| 71 | 160 | 9 |
| 82 | 255 | 10 |

**Note:**
[1]The hysteresis set for each trip point must be greater than the previous trip point. For example, 82 °C - 10 °C = 72 °C, which is greater than the 160 PWM trip point at 71 °C.

Custom fan settings can be implemented if needed, consult BSP documentation for details.

## 4.3 TEGRA X1 SOC MAXIMUM OPERATING TEMPERATURE

The recommended operating temperature limit is the threshold at which the module will operate without performance reduction. These temperatures are listed in Table 2-1 and cannot be adjusted. The customer's tolerance for performance reduction should determine the amount of $T_j$ operating headroom in the thermal solution design in order to accommodate the temperature sensor accuracy of ± 3 °C.

Software thermal management operates as follows:

- When the measured temperature is at or below the operating temperature threshold, software $T_j$ thermal management is not engaged and the system is free to vary the system frequencies and voltages.
- When the measured temperature reaches the thermal management threshold, the internal thermal sensors generate an interrupt to software. At this point the software thermal management algorithm engages and begins periodically performing the following operations:
  - Polling temperature.
  - Running a thermal management control algorithm to calculating the throttle degree, indicating the amount of throttling to apply during the next time period.
  - Throttling the system to the level of throttling indicated by the throttling control algorithm. Throttling is applied through limits on the clock frequency of high-power units such as the CPU and graphics processing unit (GPU). Higher throttling degree results in lower frequency limits. DVFS policies operate within these frequency limits.
- Software thermal management remains in operation until the Tegra X1 temperature has returned to a value below the throttling threshold and throttling degree has returned to zero.

Note that power fluctuations that induce $T_j$ fluctuations above the software thermal management thresholds will cause temporary clock reductions. Power fluctuations in the target workload should be evaluated for their potential to cause temperature to fluctuate above the software threshold.

## 4.4 TEGRA X1 HARDWARE THERMAL THROTTLING

In the event that software thermal management is not able to maintain the Tegra X1 temperature, then hardware thermal throttling will engage in an attempt to prevent thermal shutdown. To help avoid thermal shutdown conditions without being overly conservative, Tegra X1 has hardware-engaged clock throttling mechanisms that are used as a last resort to prevent shutdown conditions. This will lower the Tegra X1 temperature but it will also significantly reduce the overall Tegra X1 performance. The Tegra X1 throttle settings cannot be altered. These settings are implemented by NVIDIA to meet safety and reliability standards.

## 4.5 TEGRA X1 SHUTDOWN TEMPERATURE

Tegra X1 is rated to operate at a junction temperature not-to-exceed 105 °C. Tegra X1 has hardware shutdown mechanisms that enforce this limit by automatically halting the system when this temperature is exceeded.

The shutdown temperature should not be reached at any time during normal operation, but it may occur if cooling system components are broken, jammed, or otherwise unable to cool the Tegra X1 under worst-case conditions. If a thermal shutdown event is triggered, then a major fault in the Jetson TX1 or system cooling solution has occurred. Thermal shutdown can be initiated by any of the sensors listed in Table 2-1. Using multiple sensors enables operation closer to the temperature limit without compromising reliability by reducing the uncertainty associated with the hotspot location.

The following thermal shutdown mechanisms have been implemented:

- Internal sensor-based shutdown. Failsafe thermal shutdown is guaranteed by using the SHUTDOWN signal directly from Tegra to the PMIC. After the failsafe shutdown the user will have to manually turn the system on by pressing the power button or equivalent input.
- T.diode/temperature-monitor-based shutdown. When the external temperature monitor detects that the T.diode temperature is above a pre-programmed Tshutdown, the monitor's THERM output signals the PMIC to shut down the system without any software control. This is a back-up mechanism to the internal sensor-based shutdown, so its Tshutdown is intentionally margined to a higher temperature to avoid contention with internal sensor-based shutdown.

The Tegra X1 shutdown settings cannot be altered. These settings are implemented by NVIDIA to meet safety and reliability standards.

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