Regression Analyses for Data Synchronization between In-process Monitoring Sensors in Laser Powder Bed Fusion (LBPF) Process

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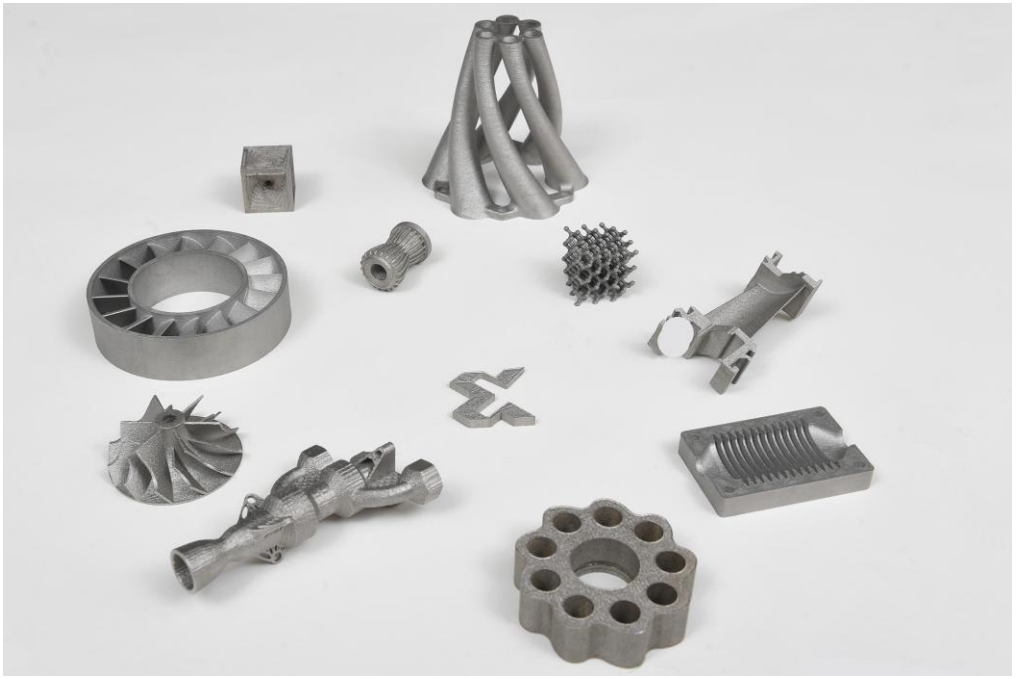
Background & Motivation

- **Laser Powder Bed Fusion (LPBF) Process:** A metal 3D printing process to fabricate parts based on a digital 3D model by selectively melting fine metal powders layer by layer.

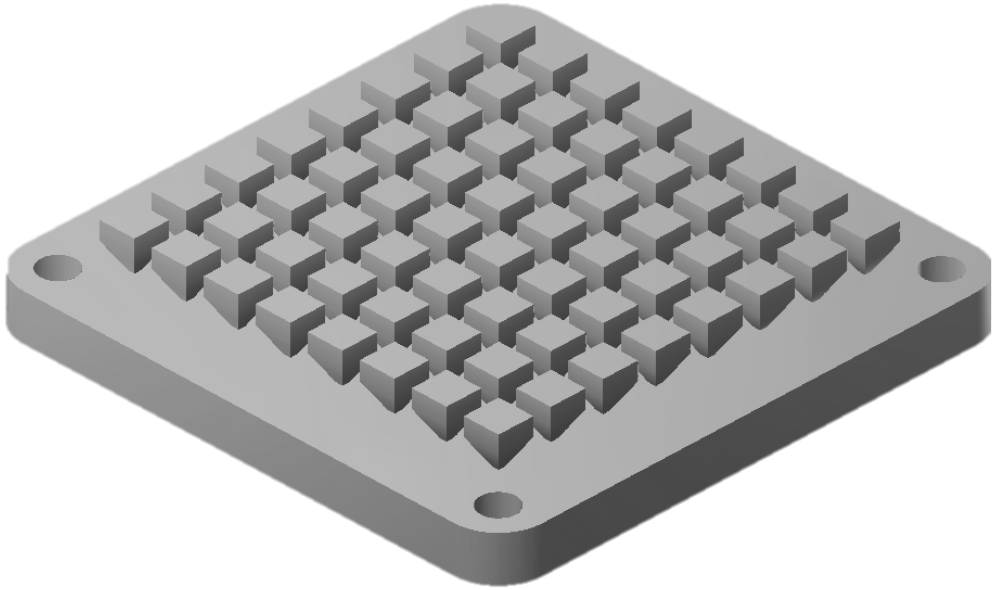


LPBF printed parts (source link)

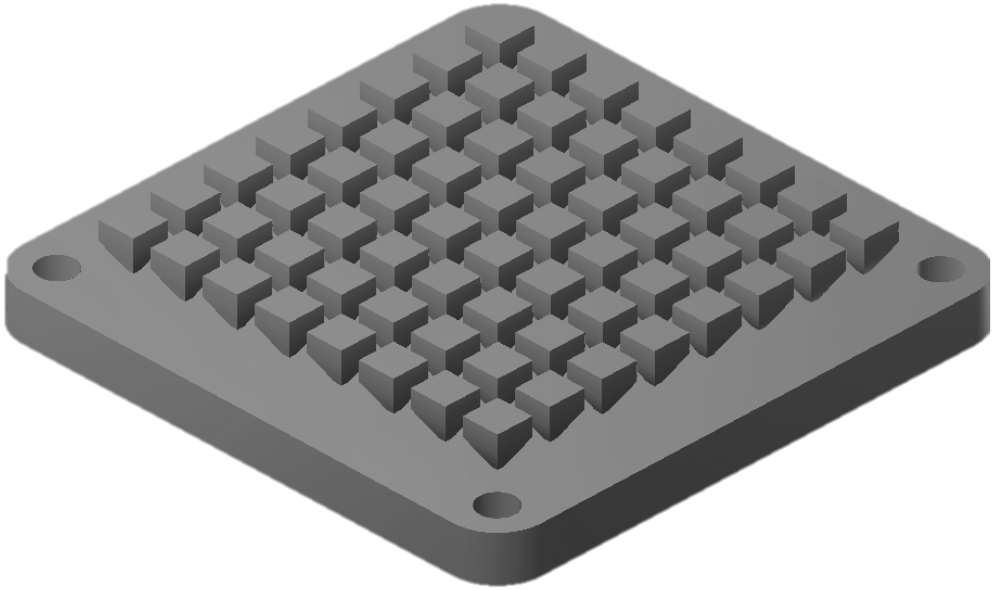
LPBF process in action (source link)

Background & Motivation

- In-process monitoring data was collected during the printing of two following parts using the following:
  - Field-Programmable Gate Array (FPGA) sensor
  - Melt Pool Monitoring (MPM) camera



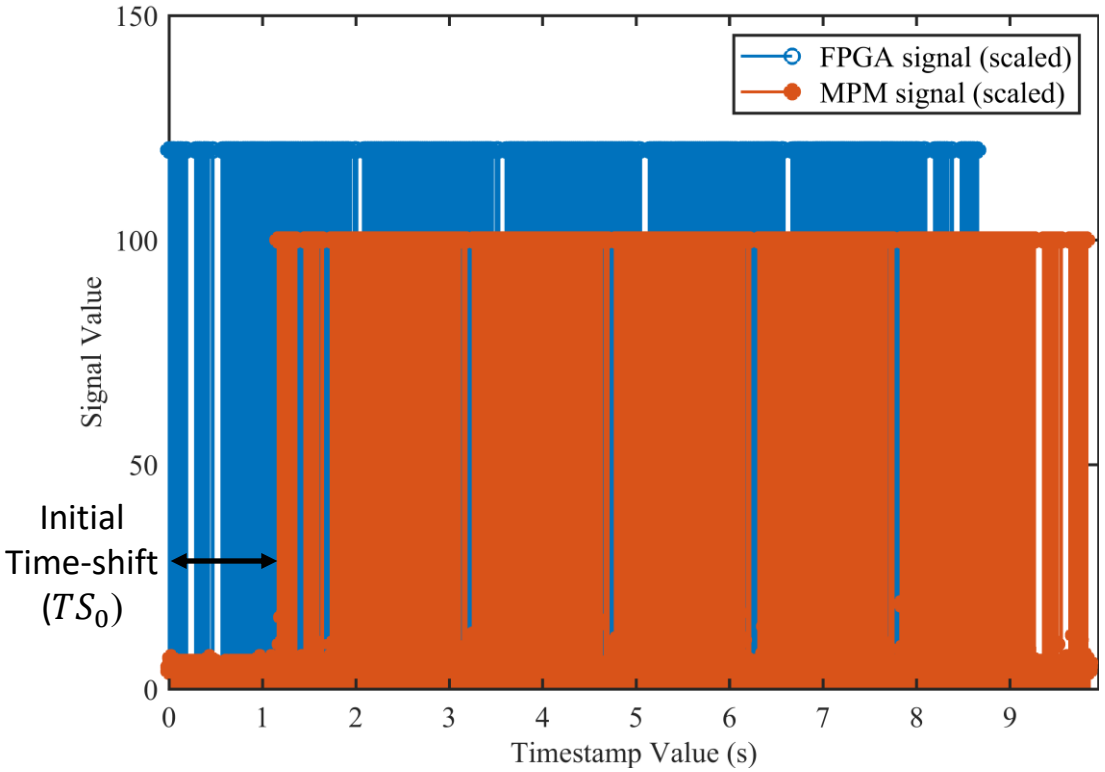
Part 1 - made of In718 alloy with 321 layers



Part 2 - made of H282 alloy with 401 layers

Background & Motivation

- In-process monitoring sensor and camera under consideration:
  - Field-Programmable Gate Array (FPGA) sensor
  - Melt Pool Monitoring (MPM) camera



FPGA and MPM data for a ***single*** **layer** within **a part**

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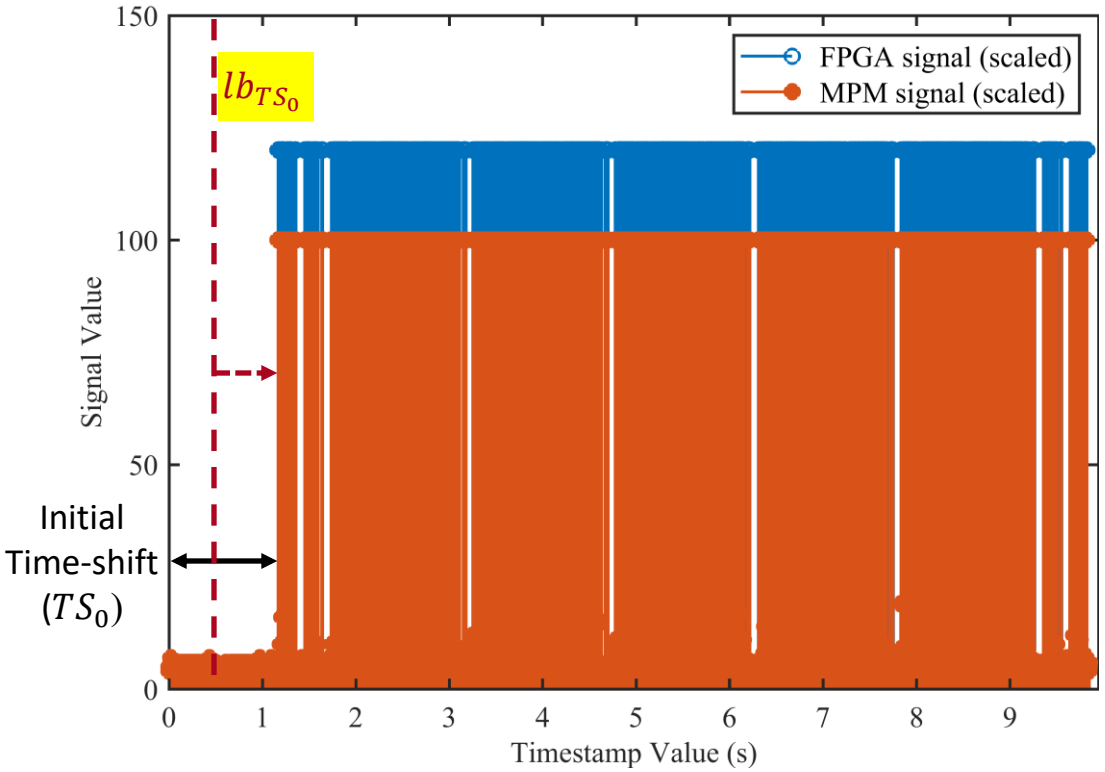


FPGA and MPM data for a ***single*** **layer** within **a part**

Research Question 1

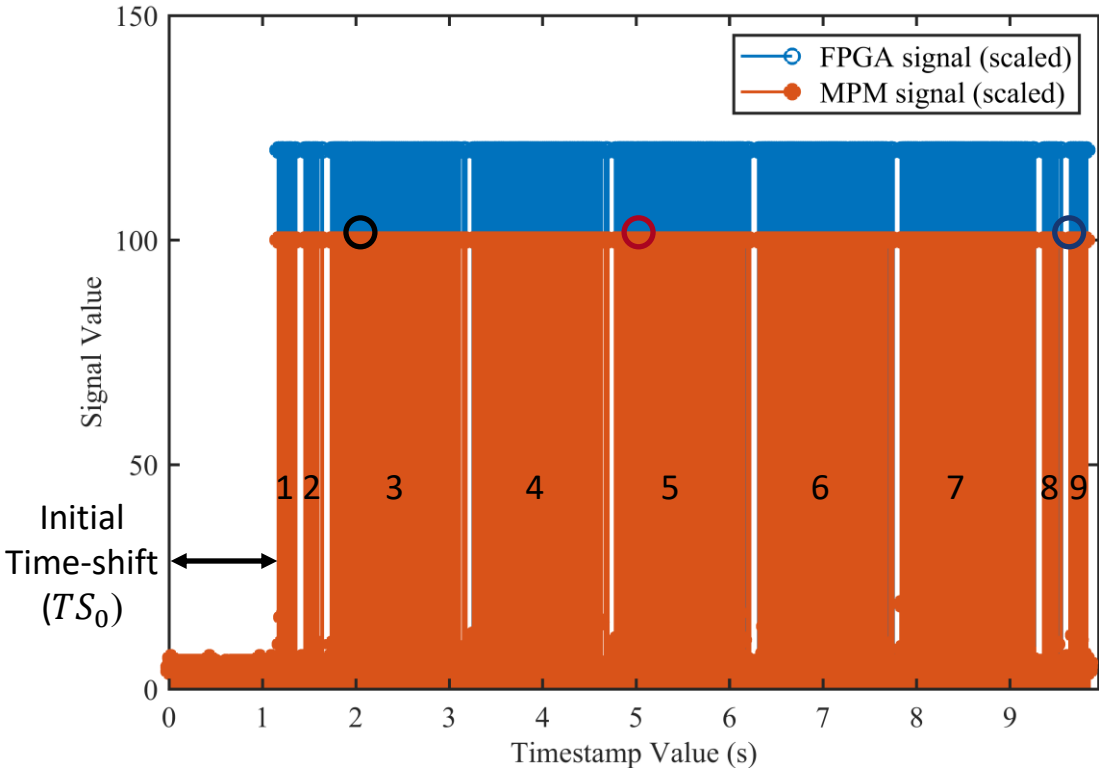
Does a statistical relationship exist among the variables "Initial time-shift, TS_0", "Layer index, L", and "Part index, P"?

Regression analysis 1: $TS_0 \sim f(L, P)$

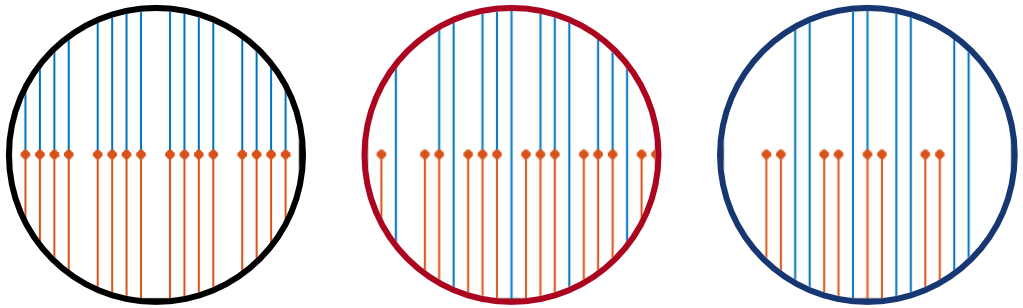
Additionally, determining a lower bound on TS_0 can help optimizing computational efficiency.

Background & Motivation

- Does the "Initial Time-shift (TS_0) Adjustment" solve the synchronization problem?
  - Answer: **NO**.
- Additional time-shift adjustment is required: $TS_i = TS_0 + \tau_i$



FPGA and MPM data for a ***single*** **layer** within **a part**



Block 3
$\tau_i = 0$

Block 5
$\tau_i = 1 \times 10^{-3}$

Block 9
$\tau_i = 2 \times 10^{-3}$

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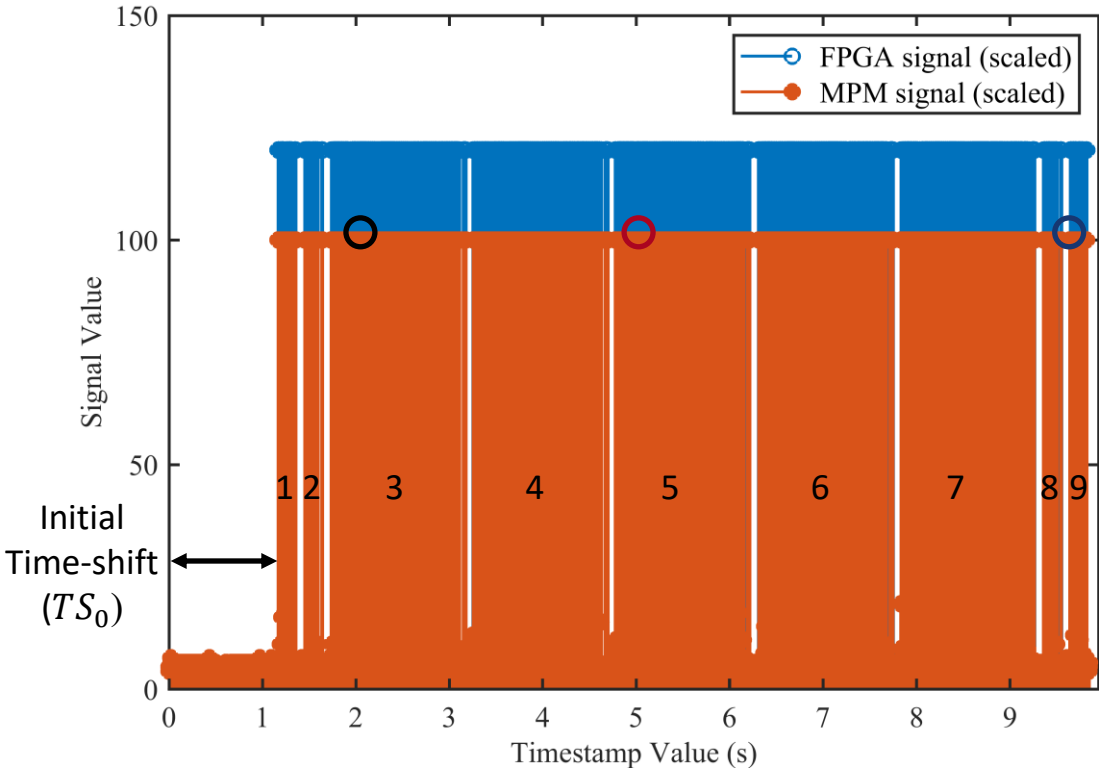

FPGA and MPM data for a ***single*** **layer** within **a part**

Research Question 2

Does a statistical relationship exist among the variables "Time-shift adjustment, τ", "FPGA timestamp, T_{FPGA}", "Initial time-shift, TS_0", "Layer index, L", and "Part index, P"?

Regression analysis 2: $\tau \sim f(T_{FPGA}, TS_0, L, P)$

Background & Motivation

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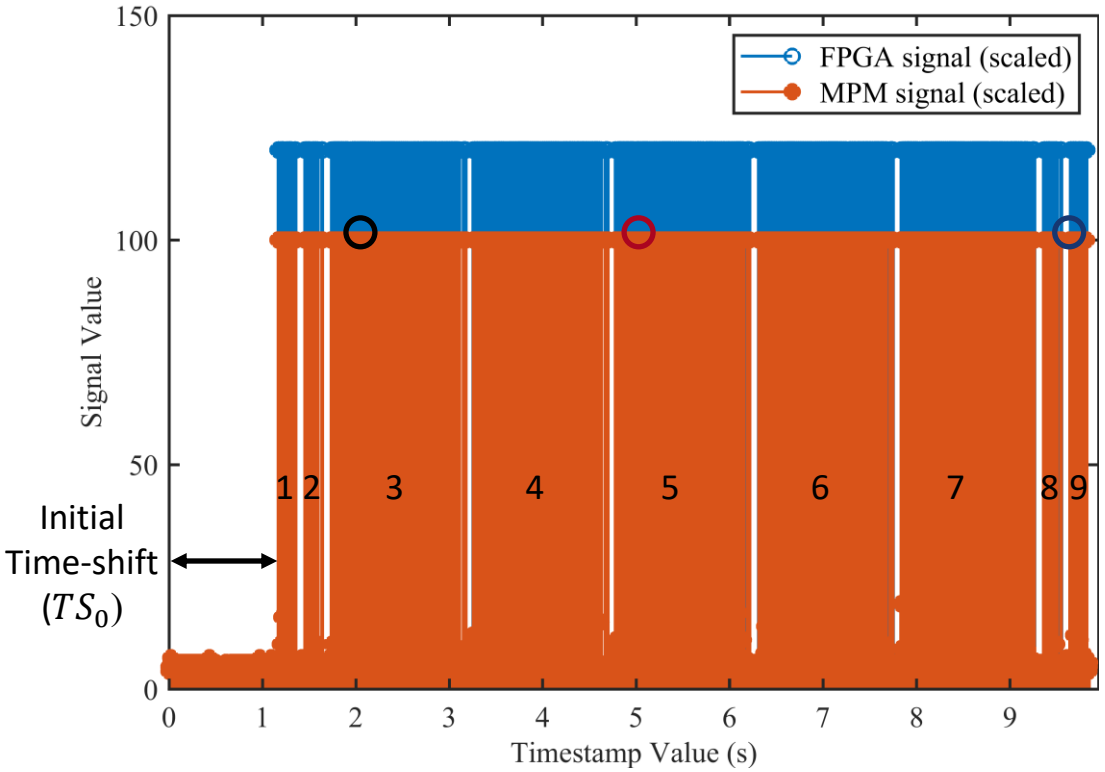


FPGA and MPM data for a ***single*** **layer** within **a part**

Research Question 3

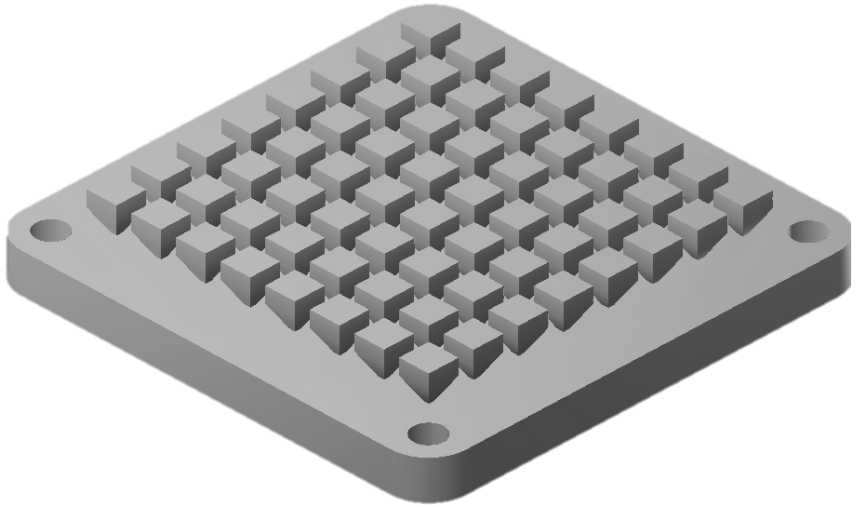
Can "Time-shift adjustment, τ" be predicted by using its statistical relationship with the predictor variables: "FPGA timestamp, T_{FPGA}", "Initial time-shift, TS_0", and "Layer index, L"?

Regression analysis 3: $\tau \sim f(T_{FPGA}, TS_0, L)$

Additionally, determining the maximum prediction-error *magnitude* can help accommodating further adjustment for accurate synchronization.

Data Collection

- For Regression Analysis 1 [$TS_0 \sim f(L, P)$]:
  - *Initial time-shift* (TS_0) values are collected from the two *parts* (P) for all *layers* (L) .
- For Regression Analysis 2 [$\tau \sim f(T_{FPGA}, TS_0, L, P)$] & 3 [$\tau \sim f(T_{FPGA}, TS_0, L, P)$]:
  - *Time-shift adjustments* (τ) values across *FPGA timestamps* (T_{FPGA}) are collected from the two *parts* (P) for selected *layers* (L) along with associated *initial time-shift* (TS_0) values.



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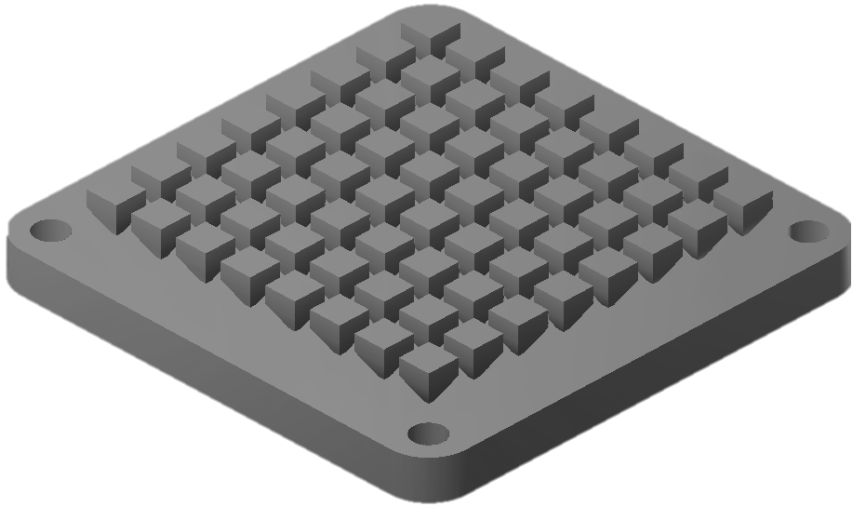
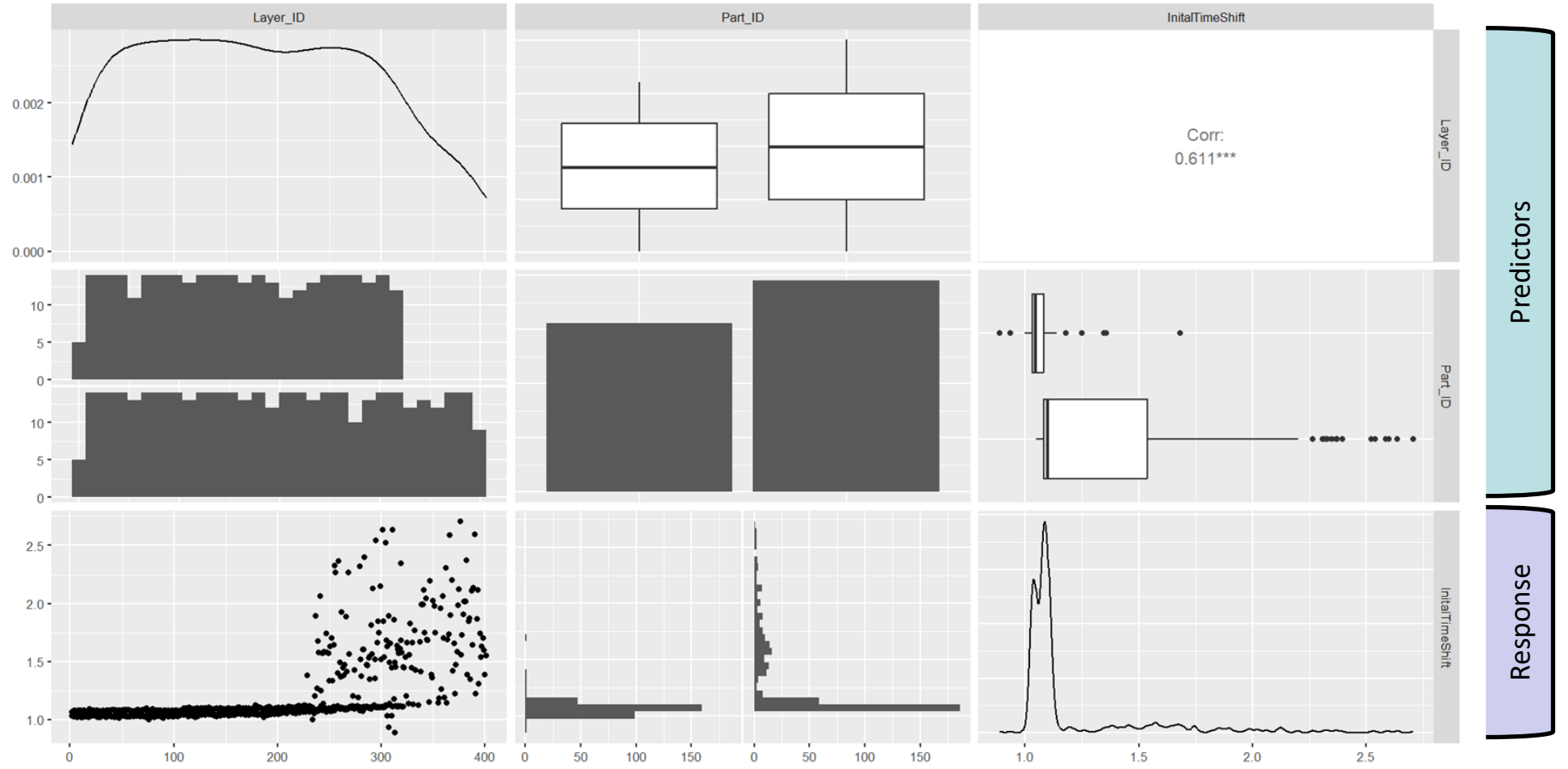


Part 2 - made of H282 alloy with 401 layers

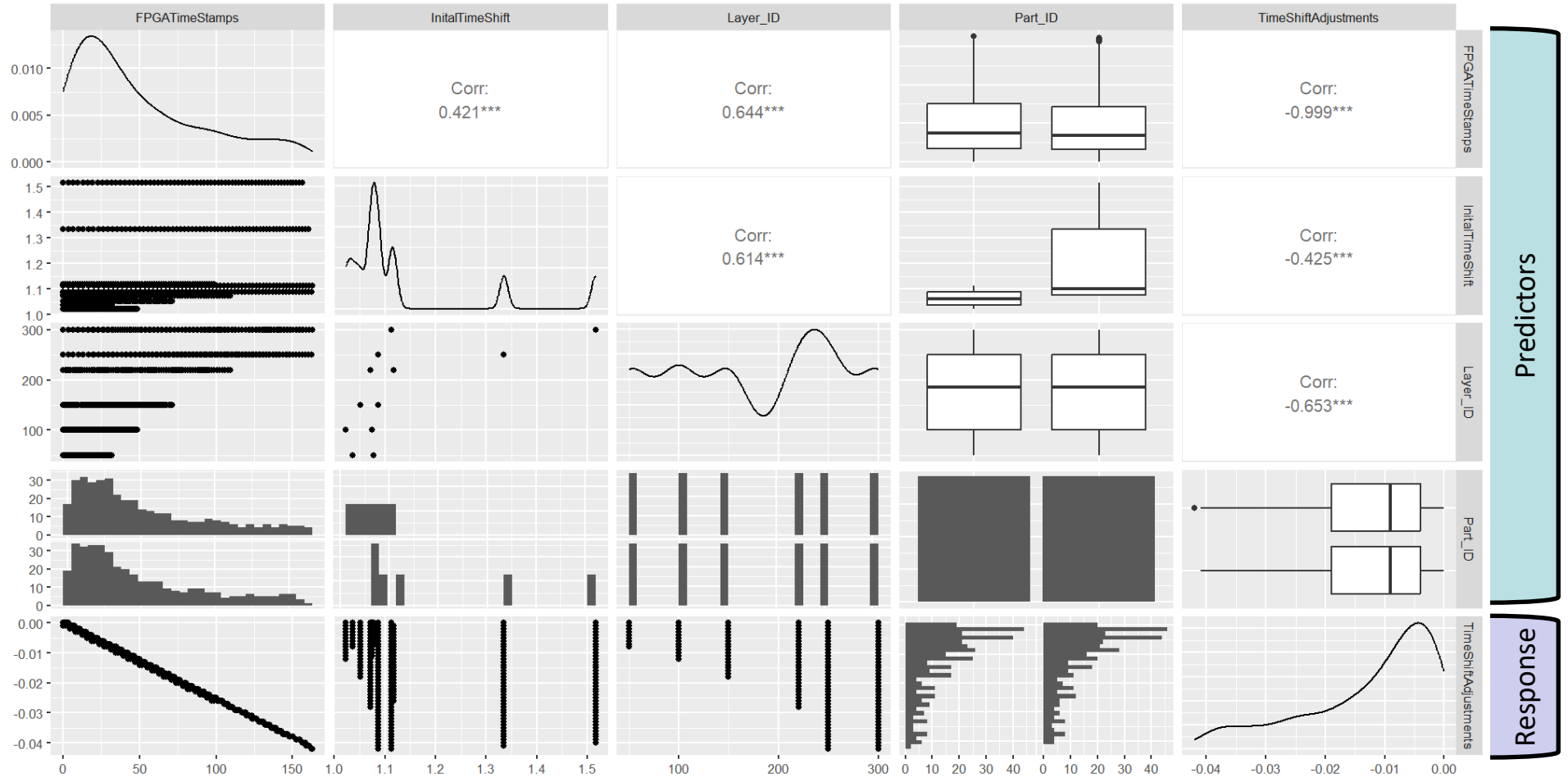
Data Exploration

- For Regression Analysis 1 [$TS_0 \sim f(L, P)$]:



Data Exploration

- For Regression Analysis 2 [$\tau \sim f(T_{FPGA}, TS_0, L, P)$] & 3 [$\tau \sim f(T_{FPGA}, TS_0, L, P)$]:



Data Exploration

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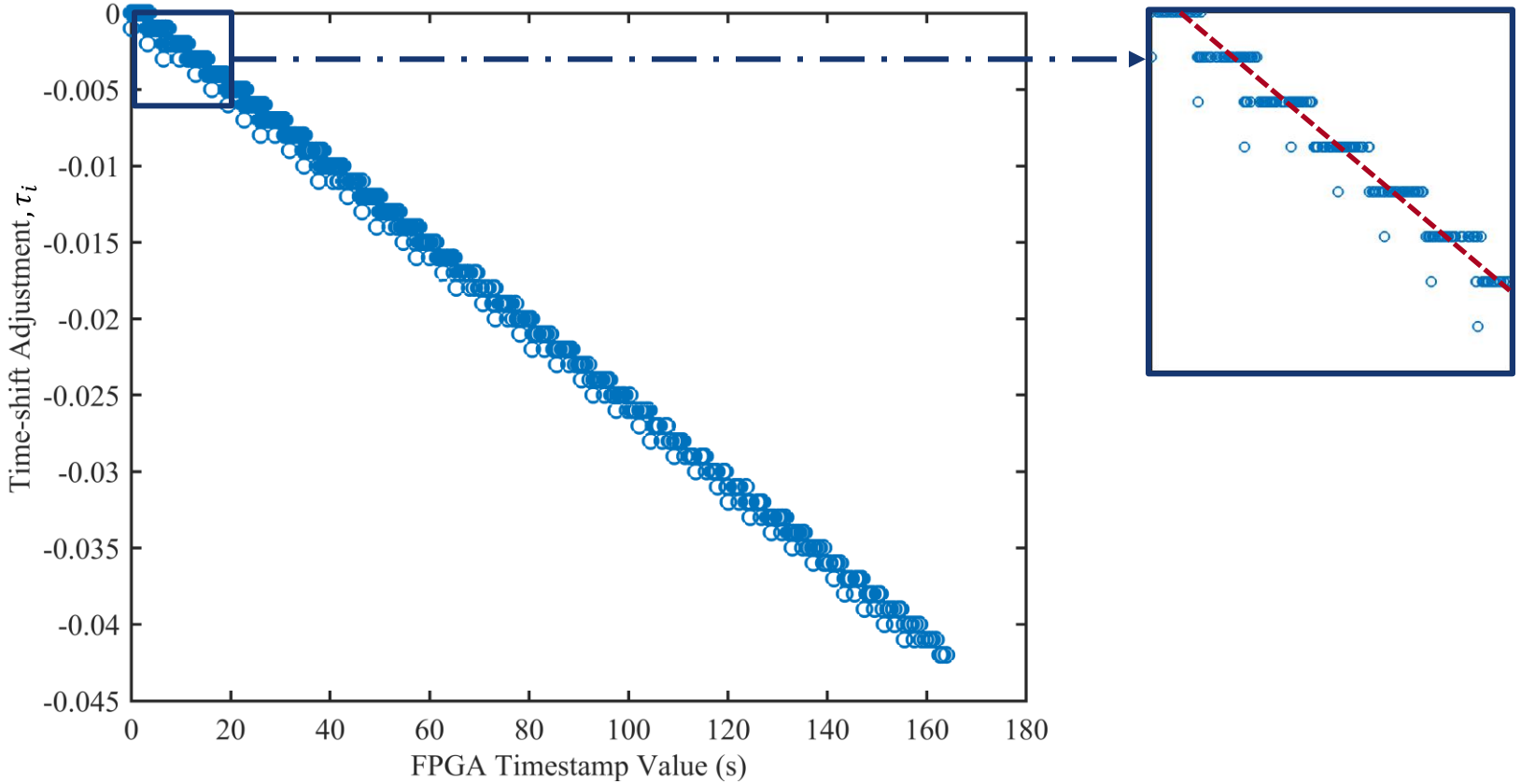


Results and Discussion

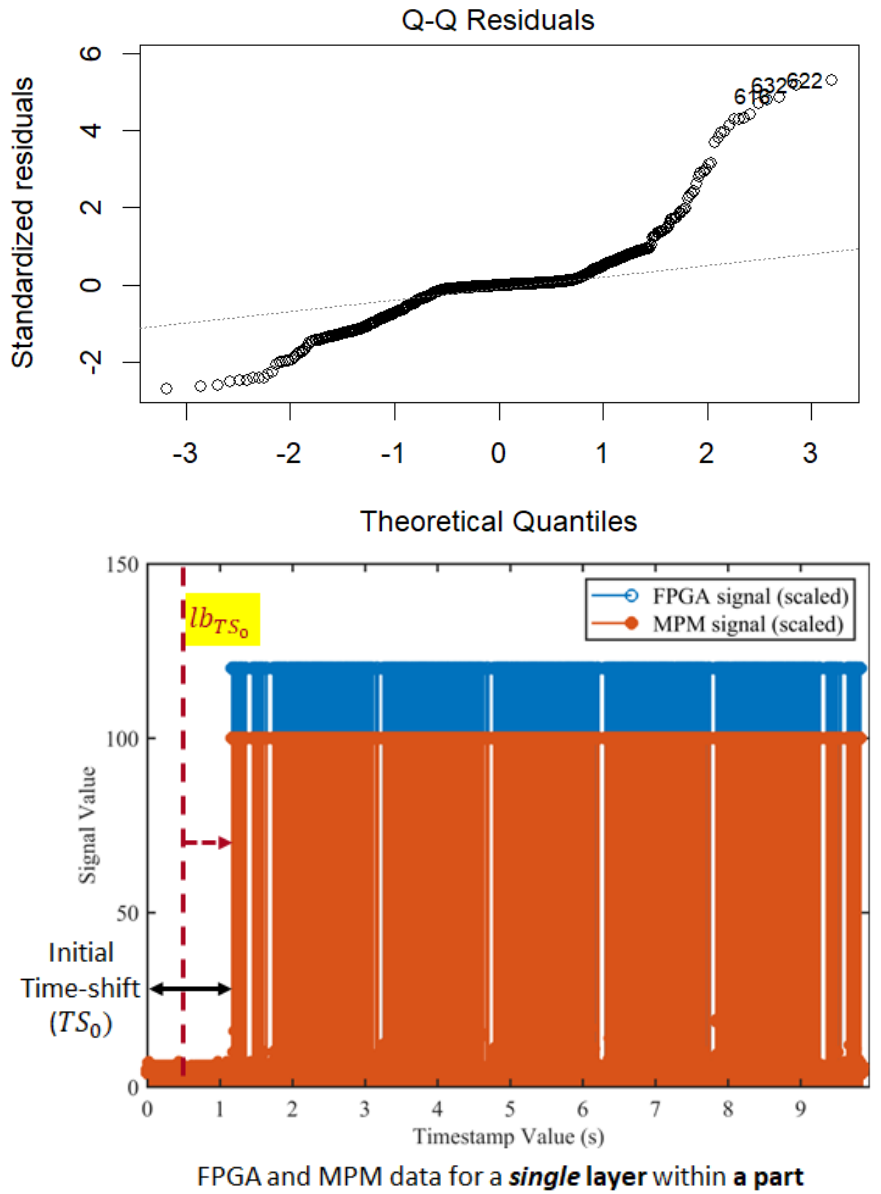
- Regression Analysis 1 [$TS_0 \sim f(L, P)$]
  - **Answer to Research Question 1:** Does a statistical relationship exist among the variables "Initial time-shift, TS_0", "Layer index, L", and "Part index, P"?

```
TS0_formula <- (InitalTimeShift ~ Layer_ID + Part_ID + Layer_ID:Part_ID)
model_TS0_all <- lm(TS0_formula, data = df_TS0)
summary(model_TS0_all)
```

```
##
## Call:
## lm(formula = TS0_formula, data = df_TS0)
##
## Residuals:
##      Min       1Q   Median       3Q      Max
## -0.55106 -0.06097 -0.00399  0.02038  1.08003
##
## Coefficients:
##                           Estimate Std. Error t value Pr(>|t|)
## (Intercept)             1.0063053  0.0232055  43.365  < 2e-16 ***
## Layer_ID                0.0003313  0.0001247   2.657  0.00806 **
## Part_IDPart 2          -0.1294588  0.0310462  -4.170 3.43e-05 ***
## Layer_ID:Part_IDPart 2  0.0019283  0.0001535  12.566  < 2e-16 ***
```

Results and Discussion

- Regression Analysis 1 [$TS_0 \sim f(L, P)$]
  - **Determination of lower bound on TS_0:**
    - Q-Q plot reveals that normality assumption is not valid.
    - "Bootstrapping" is implemented to obtain 99% confidence interval on the predicted values for TS_0.
    - Obtained *lowest* bound, lb_{TS_0}: **0.881** s.
    - *Implication*: **881** frames from the MPM camera video (1000 fps) can be skipped and thus the computational burden can be reduced.



FPGA and MPM data for a ***single*** **layer** within **a part**

Results and Discussion

- Regression Analysis 2 $[\tau \sim f(T_{FPGA}, TS_0, L, P)]$
  - **Answer to Research Question 2:** Does a statistical relationship exist among the variables "Time-shift adjustment, τ", "FPGA timestamp, T_{FPGA}", "Initial time-shift, TS_0", "Layer index, L", and "Part index, P"?

```
tau_formula_initial <- (TimeShiftAdjustments ~ FPGATimeStamps + InitalTimeShift +
                  Layer_ID + Part_ID + FPGATimeStamps:InitalTimeShift +
                  FPGATimeStamps:Layer_ID + FPGATimeStamps:Part_ID +
                  InitalTimeShift:Layer_ID + InitalTimeShift:Part_ID +
                  Layer_ID:Part_ID )

model_initial <- lm(tau_formula_initial, data = df_tau)
summary(model_initial)
```

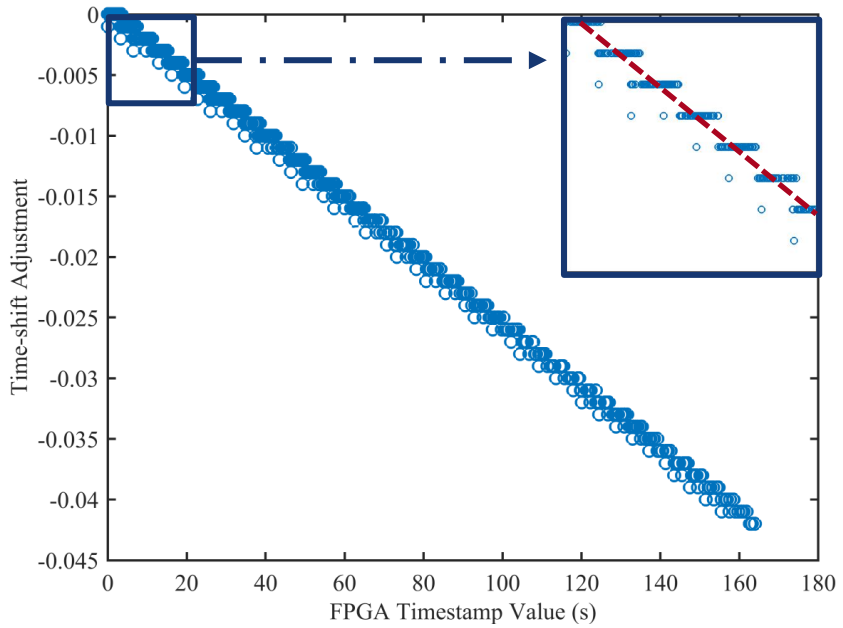
```
##
## Call:
## lm(formula = tau_formula_initial, data = df_tau)
##
## Residuals:
##        Min         1Q     Median         3Q        Max
## -8.031e-04 -2.559e-04 -4.170e-06  2.521e-04  8.370e-04
##
## Coefficients:
##                                  Estimate Std. Error t value Pr(>|t|)
## (Intercept)                    -2.754e-03  2.197e-03  -1.254 0.210260
## FPGATimeStamps                 -2.659e-04  3.829e-06 -69.464  < 2e-16 ***
## InitalTimeShift                 2.981e-03  2.158e-03   1.381 0.167571
## Layer_ID                        9.558e-06  4.283e-06   2.232 0.025931 *
## Part_IDPart 2                  -1.622e-03  2.015e-03  -0.805 0.421068
## FPGATimeStamps:InitalTimeShift  1.555e-05  4.410e-06   3.527 0.000446 ***
## FPGATimeStamps:Layer_ID        -2.634e-08  8.534e-09  -3.086 0.002100 **
## FPGATimeStamps:Part_IDPart 2   -3.422e-06  1.326e-06  -2.581 0.010034 *
## InitalTimeShift:Layer_ID       -9.845e-06  4.077e-06  -2.415 0.015990 *
## InitalTimeShift:Part_IDPart 2   1.898e-03  1.990e-03   0.953 0.340680
## Layer_ID:Part_IDPart 2         -4.970e-06  7.995e-07  -6.217 8.39e-10 ***
```

Results and Discussion

- Regression Analysis 3 $[\tau \sim f(T_{FPGA}, TS_0, L)]$
  - **Answer to Research Question 3:** Can "Time-shift adjustment, τ" be predicted by using its statistical relationship with the predictor variables: "FPGA timestamp, T_{FPGA}", "Initial time-shift, TS_0", and "Layer index, L"?
    - **3 candidate models** were selected, and their prediction accuracy was evaluated using 10-fold cross validation.
      1. **Full model:** Include all main effects and interaction effects of the predictor variables.
      2. **Lasso-penalized model:** "cv.glmnet" with LASSO penalty is employed to select the model that corresponds to the minimum mean-squared error across a 10-fold cross-validation.
      3. **Step-wise regression model:** Step-wise regression in both direction is used to select the model based on AIC (Akaike's information criterion) metric.

Results and Discussion

- Regression Analysis 3 $[\tau \sim f(T_{FPGA}, TS_0, L)]$
  - **Answer to Research Question 3:** Can "Time-shift adjustment, τ" be predicted by using its statistical relationship with the predictor variables: "FPGA timestamp, T_{FPGA}", "Initial time-shift, TS_0", and "Layer index, L"?
    - **Prediction-accuracy calculation:**

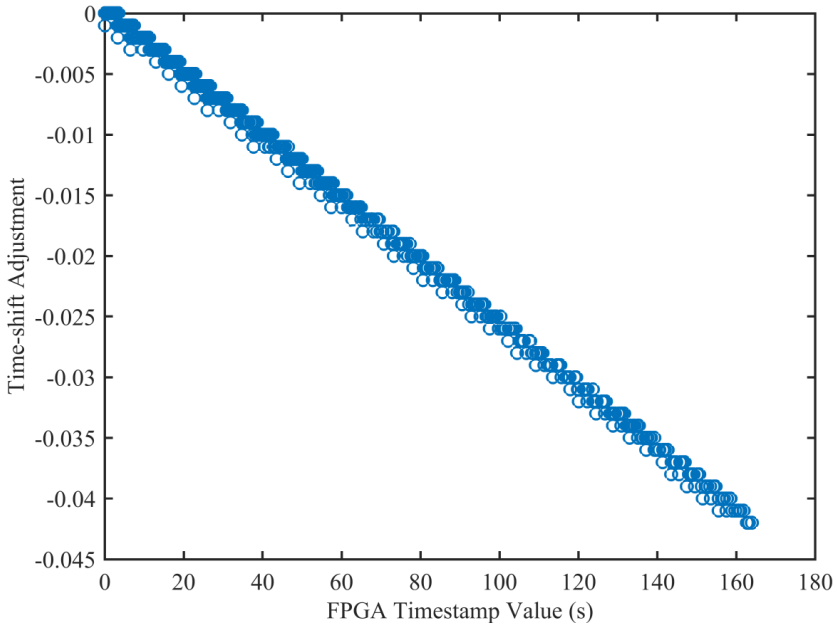



```r
for (i in 1:k) {
  test_indices <- random_indices[fold_indices == i]
  train_data <- df_tau[-test_indices, ]
  test_data <- df_tau[test_indices, ]

  # Fit the model_full on the training data
  model_full <- lm(tau_formula, data = train_data)

  # Make predictions on the test data
  predictions <- predict(model_full, newdata = test_data)

  # calculate errors (after appropriate rounding), and accuracy %
  errors <- test_data[,5] - round(predictions,3)
  pct_accuracy <- length(which(errors==0))/nrow(test_data)*100
  cv_pct_accuracy[i] <- pct_accuracy
}
```

Results and Discussion

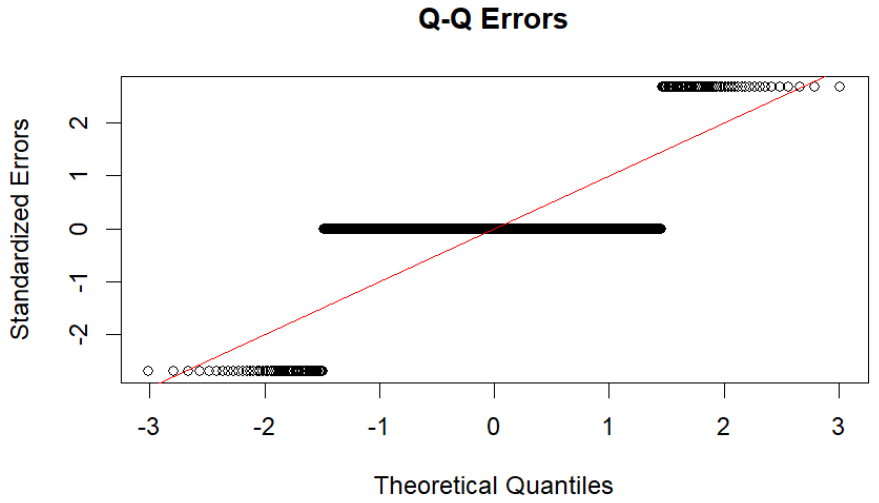
- Regression Analysis 3 $[\tau \sim f(T_{FPGA}, TS_0, L)]$
  - **Answer to Research Question 3:** Can "Time-shift adjustment, τ" be predicted by using its statistical relationship with the predictor variables: "FPGA timestamp, T_{FPGA}", "Initial time-shift, TS_0", and "Layer index, L"?

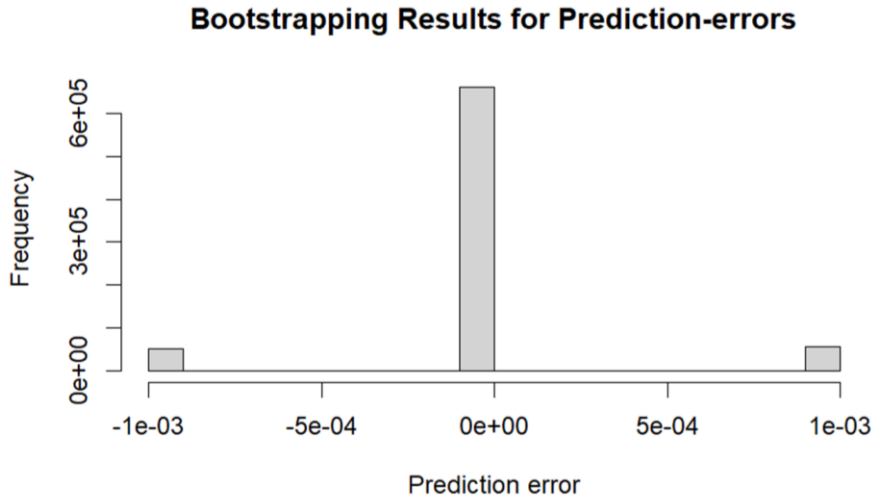
Model	Average Cross-validation Accuracy
Full model	72.80075%
Lasso-penalized model ($\tau \sim T_{FPGA} + L$)	**74.09945%**
Step-wise regression model ($\tau \sim T_{FPGA} + TS_0 + L + T_{FPGA} * L + TS_0 * L$)	73.06049%
Base model ($\tau \sim T_{FPGA}$)	70.45455%



Results and Discussion

- Regression Analysis 3 $[\tau \sim f(T_{FPGA}, TS_0, L)]$
  - **Determination of the *maximum prediction-error magnitude*:**
    - Q-Q plot reveals that normality assumption is not valid for the discretized errors or residuals.
    - "Bootstrapping" is implemented to obtain 99% confidence interval on the prediction-errors: CI_{error} = $[-0.001, 0.001]$ s.
    - *Implication*: After obtaining the prediction for τ_i, synchronization results will be checked for τ_i and $(\tau_i \pm 0.001)$ to confirm the accurate synchronization.





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