

# Revisiting the Available Cases Method for Missing Values

Xiao (Max) Gu and Norm Matloff  
University of California at Davis

JSM 2015

# Taxonomy of Methods

# Taxonomy of Methods

Major current methods:

# Taxonomy of Methods

Major current methods:

- Use only complete cases (CC).
- Multiple imputation (MI).
- MLE.

# Taxonomy of Methods

Major current methods:

- Use only complete cases (CC).
- Multiple imputation (MI).
- MLE.

Forgotten method:

# Taxonomy of Methods

## Major current methods:

- Use only complete cases (CC).
- Multiple imputation (MI).
- MLE.

## Forgotten method:

- Available cases (AC). Use partially-intact cases when possible.

# Overview of AC Method

Xiao (Max)  
Gu and Norm  
Matloff  
University of  
California at  
Davis

## Overview of AC Method

E.g. linear regression (random-X).

## Overview of AC Method

E.g. linear regression (random-X).

$$\hat{\beta} = (X'X)^{-1}X'Y = \left[ \frac{1}{n}(X'X)^{-1} \right] \left[ \frac{1}{n}X'Y \right] = A^{-1}D \quad (1)$$

## Overview of AC Method

E.g. linear regression (random-X).

$$\hat{\beta} = (X'X)^{-1}X'Y = \left[ \frac{1}{n}(X'X)^{-1} \right] \left[ \frac{1}{n}X'Y \right] = A^{-1}D \quad (1)$$

$A$  estimates quantities like

## Overview of AC Method

E.g. linear regression (random-X).

$$\hat{\beta} = (X'X)^{-1}X'Y = \left[ \frac{1}{n}(X'X)^{-1} \right] \left[ \frac{1}{n}X'Y \right] = A^{-1}D \quad (1)$$

$A$  estimates quantities like

$$E[X^{(i)}X^{(j)}] \quad (2)$$

## Overview of AC Method

E.g. linear regression (random- $X$ ).

$$\hat{\beta} = (X'X)^{-1}X'Y = \left[ \frac{1}{n}(X'X)^{-1} \right] \left[ \frac{1}{n}X'Y \right] = A^{-1}D \quad (1)$$

$A$  estimates quantities like

$$E[X^{(i)}X^{(j)}] \quad (2)$$

while  $D$  estimates quantities like

## Overview of AC Method

E.g. linear regression (random- $X$ ).

$$\hat{\beta} = (X'X)^{-1}X'Y = \left[ \frac{1}{n}(X'X)^{-1} \right] \left[ \frac{1}{n}X'Y \right] = A^{-1}D \quad (1)$$

$A$  estimates quantities like

$$E[X^{(i)}X^{(j)}] \quad (2)$$

while  $D$  estimates quantities like

$$E[X^{(i)}Y] \quad (3)$$

# AC Overview, cont'd.

## AC Overview, cont'd.

**CC seems wasteful.**

### **CC seems wasteful.**

- In estimating, say,  $E[X^{(2)}Y]$ , why throw out cases in which  $X^{(2)}$  and  $Y$  are intact but  $X^{(5)}$  is missing?

## AC Overview, cont'd.

### CC seems wasteful.

- In estimating, say,  $E[X^{(2)}Y]$ , why throw out cases in which  $X^{(2)}$  and  $Y$  are intact but  $X^{(5)}$  is missing?
- Instead, estimate by  $E[X^{(i)}Y]$  by

$$\frac{1}{M} \sum_{X^{(i)}, Y \text{ intact}} X_k^{(i)} Y_k \quad (4)$$

where  $M = \#$  of cases with both  $X^{(i)}$  and  $Y$  intact.

## AC Overview, cont'd.

### CC seems wasteful.

- In estimating, say,  $E[X^{(2)}Y]$ , why throw out cases in which  $X^{(2)}$  and  $Y$  are intact but  $X^{(5)}$  is missing?
- Instead, estimate by  $E[X^{(i)}Y]$  by

$$\frac{1}{M} \sum_{X^{(i)}, Y \text{ intact}} X_k^{(i)} Y_k \quad (4)$$

where  $M = \#$  of cases with both  $X^{(i)}$  and  $Y$  intact.

- Same for the quantities  $E[X^{(i)}X^{(j)}]$ .

# AC Sounds Good, But Not Popular

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature,

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:
  - The modified  $X'X$  may not be positive definite.

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:
  - The modified  $X'X$  may not be positive definite.
  - AC assumes MCAR, the strongest among the famous assumption sets.

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:
  - The modified  $X'X$  may not be positive definite.
  - AC assumes MCAR, the strongest among the famous assumption sets.
- Still, AC seems worth revisiting.

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:
  - The modified  $X'X$  may not be positive definite.
  - AC assumes MCAR, the strongest among the famous assumption sets.
- Still, AC seems worth revisiting.
  - Lack of positive definiteness is unlikely to occur, and it's unclear whether it's important anyway.

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:
  - The modified  $X'X$  may not be positive definite.
  - AC assumes MCAR, the strongest among the famous assumption sets.
- Still, AC seems worth revisiting.
  - Lack of positive definiteness is unlikely to occur, and it's unclear whether it's important anyway.
  - The most common alternative assumption set, MAR, is also quite strong.

## AC Sounds Good, But Not Popular

- AC should be more accurate than CC — uses more data.
- Yet, AC seems to have been dismissed early on in the Missing Value literature, apparently because:
  - The modified  $X'X$  may not be positive definite.
  - AC assumes MCAR, the strongest among the famous assumption sets.
- Still, AC seems worth revisiting.
  - Lack of positive definiteness is unlikely to occur, and it's unclear whether it's important anyway.
  - The most common alternative assumption set, MAR, is also quite strong. (More on this later.)

# Our Study: AC vs. CC, MI

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC,

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression,

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression, and 2 new ones: PCA and log-linear model.

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression, and 2 new ones: PCA and log-linear model.
- We look at these criteria:

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression, and 2 new ones: PCA and log-linear model.
- We look at these criteria:
  - Applicability.

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression, and 2 new ones: PCA and log-linear model.
- We look at these criteria:
  - Applicability.
  - Variance, bias.

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression, and 2 new ones: PCA and log-linear model.
- We look at these criteria:
  - Applicability.
  - Variance, bias.
  - Run time.

## Our Study: AC vs. CC, MI

- Here we “reopen the case” regarding AC, comparing to CC and MI.
- We look at the old application, linear regression, and 2 new ones: PCA and log-linear model.
- We look at these criteria:
  - Applicability.
  - Variance, bias.
  - Run time.
- For MI, we use Amelia 2.

# Linear Regression

# Linear Regression

- All 3 methods are applicable.

# Linear Regression

- All 3 methods are applicable.
- Simulation results:  $n = 10000$ ,  $p = 3$ , 10% missing,  
 $\beta_1 = 1$

## Linear Regression

- All 3 methods are applicable.
- Simulation results:  $n = 10000$ ,  $p = 3$ , 10% missing,

$$\beta_1 = 1$$

method	mean	variance	time
CC	0.9996	0.0002	0.79
MI	0.9784	0.0002	142.02
AC	1.0027	0.0010	23.80

Note: Most time in AC spent in finding numeric derivs for standard errors.

## Linear Regression

- All 3 methods are applicable.
- Simulation results:  $n = 10000$ ,  $p = 3$ , 10% missing,

$$\beta_1 = 1$$

method	mean	variance	time
CC	0.9996	0.0002	0.79
MI	0.9784	0.0002	142.02
AC	1.0027	0.0010	23.80

Note: Most time in AC spent in finding numeric derivs for standard errors.

- MI slightly biased.

## Linear Regression

- All 3 methods are applicable.
- Simulation results:  $n = 10000$ ,  $p = 3$ , 10% missing,

$$\beta_1 = 1$$

method	mean	variance	time
CC	0.9996	0.0002	0.79
MI	0.9784	0.0002	142.02
AC	1.0027	0.0010	23.80

Note: Most time in AC spent in finding numeric derivs for standard errors.

- MI slightly biased.
- AC terrible MSE. (Some intuition....)

## Linear Regression

- All 3 methods are applicable.
- Simulation results:  $n = 10000$ ,  $p = 3$ , 10% missing,

$$\beta_1 = 1$$

method	mean	variance	time
CC	0.9996	0.0002	0.79
MI	0.9784	0.0002	142.02
AC	1.0027	0.0010	23.80

Note: Most time in AC spent in finding numeric derivs for standard errors.

- MI slightly biased.
- AC terrible MSE. (Some intuition....)
- MI terrible run time.

## Linear Regression

- All 3 methods are applicable.
- Simulation results:  $n = 10000$ ,  $p = 3$ , 10% missing,

$$\beta_1 = 1$$

method	mean	variance	time
CC	0.9996	0.0002	0.79
MI	0.9784	0.0002	142.02
AC	1.0027	0.0010	23.80

Note: Most time in AC spent in finding numeric derivs for standard errors.

- MI slightly biased.
- AC terrible MSE. (Some intuition....)
- MI terrible run time.
- Verdict: Use CC.

Revisiting the  
Available  
Cases Method  
for Missing  
Values

Xiao (Max)  
Gu and Norm  
Matloff  
University of  
California at  
Davis

# PCA

- CC, AC methods applicable.

- CC, AC methods applicable.
- MI sometimes gave error message (“perfectly collinear...”).

- CC, AC methods applicable.
- MI sometimes gave error message (“perfectly collinear...”).  
.
- Simulation results:  $n = 100$ ,  $p = 10$ , 10% missing; largest eigenvalue;  $\rho$  matrix

# PCA

- CC, AC methods applicable.
- MI sometimes gave error message (“perfectly collinear...”).
- Simulation results:  $n = 100$ ,  $p = 10$ , 10% missing; largest eigenvalue;  $\rho$  matrix

method	mean	variance
CC	2.3328	0.0517
AC	2.1012	0.0218

# PCA

- CC, AC methods applicable.
- MI sometimes gave error message (“perfectly collinear...”).
- Simulation results:  $n = 100$ ,  $p = 10$ , 10% missing; largest eigenvalue;  $\rho$  matrix

method	mean	variance
CC	2.3328	0.0517
AC	2.1012	0.0218

# A Note on PCA

## A Note on PCA

- PCA is upward biased anyway (even with no NAs), since PCA naturally overfits.

## A Note on PCA

- PCA is upward biased anyway (even with no NAs), since PCA naturally overfits. (First comp. maxes var. of lin. combs. of length 1.)

## A Note on PCA

- PCA is upward biased anyway (even with no NAs), since PCA naturally overfits. (First comp. maxes var. of lin. combs. of length 1.)
- The means of 2.1 and 2.3 we got for  $n = 100$  become about 1.97 for  $n = 1000$ .

## A Note on PCA

- PCA is upward biased anyway (even with no NAs), since PCA naturally overfits. (First comp. maxes var. of lin. combs. of length 1.)
- The means of 2.1 and 2.3 we got for  $n = 100$  become about 1.97 for  $n = 1000$ .
- But in all simulation runs, AC was *less* upward biased, and had small variance, compared to CC.

## A Note on PCA

- PCA is upward biased anyway (even with no NAs), since PCA naturally overfits. (First comp. maxes var. of lin. combs. of length 1.)
- The means of 2.1 and 2.3 we got for  $n = 100$  become about 1.97 for  $n = 1000$ .
- But in all simulation runs, AC was *less* upward biased, and had small variance, compared to CC. This was severe for larger values of  $p$ .

# Contingency Table Models

## Contingency Table Models

- MI not appropriate, since assumes MV normal data.

## Contingency Table Models

- MI not appropriate, since assumes MV normal data.  
(Though MI methods do exist for this setting.)

## Contingency Table Models

- MI not appropriate, since assumes MV normal data. (Though MI methods do exist for this setting.)
- Example: Factors  $X, Y, Z$ ;

## Contingency Table Models

- MI not appropriate, since assumes MV normal data. (Though MI methods do exist for this setting.)
- Example: Factors  $X, Y, Z$ ; (12)(13) model —  $Y$  and  $Z$  independent, given  $X$ .

## Contingency Table Models

- MI not appropriate, since assumes MV normal data. (Though MI methods do exist for this setting.)
- Example: Factors  $X, Y, Z$ ; (12)(13) model —  $Y$  and  $Z$  independent, given  $X$ .
- In terms of marginal distributions:

$$p_{ijk} = p_{i..} \frac{p_{i.j} p_{i.k}}{p_{i..}} = \frac{p_{i.j} p_{i.k}}{p_{i..}} \quad (5)$$

- E.g. set  $\hat{p}_{i.k}$  to the proportion of cases in which  $X = i, Z = k$ , among cases in which  $X$  and  $Z$  are intact.
- Simulation example: (1)(23) model,  $n = 100$ , est.  $p_{111}$ .

method	mean	var
CC	0.1246591	0.0009020450
AC	0.1249168	0.0007548656

## Contingency Table Models

- MI not appropriate, since assumes MV normal data. (Though MI methods do exist for this setting.)
- Example: Factors  $X, Y, Z$ ; (12)(13) model —  $Y$  and  $Z$  independent, given  $X$ .
- In terms of marginal distributions:

$$p_{ijk} = p_{i..} \frac{p_{i.j} p_{i.k}}{p_{i..}} = \frac{p_{i.j} p_{i.k}}{p_{i..}} \quad (5)$$

- E.g. set  $\hat{p}_{i.k}$  to the proportion of cases in which  $X = i, Z = k$ , among cases in which  $X$  and  $Z$  are intact.
- Simulation example: (1)(23) model,  $n = 100$ , est.  $p_{111}$ .

method	mean	var
CC	0.1246591	0.0009020450
AC	0.1249168	0.0007548656

AC advantage more if have more factors or higher NA %.

# On Assumptions

# On Assumptions

- CC, AC assume MCAR, stronger than MI's MAR.

# On Assumptions

- CC, AC assume MCAR, stronger than MI's MAR.
- However:

## On Assumptions

- CC, AC assume MCAR, stronger than MI's MAR.
- However:
  - Arguably,  $MAR \cap MCAR^c$  rare in practice.

## On Assumptions

- CC, AC assume MCAR, stronger than MI's MAR.
- However:
  - Arguably,  $MAR \cap MCAR^c$  rare in practice.
  - $\hat{\beta}$  still unbiased for  $\beta$  under CC, AC even under  $MAR \cap MCAR^c$ .

## On Assumptions

- CC, AC assume MCAR, stronger than MI's MAR.
- However:
  - Arguably,  $MAR \cap MCAR^c$  rare in practice.
  - $\hat{\beta}$  still unbiased for  $\beta$  under CC, AC even under  $MAR \cap MCAR^c$ .
  - In  $MAR \cap MCAR^c$  case, bias does arise if use CC or AC to estimate  $EY$  or  $EX^{(i)}$ .

## On Assumptions

- CC, AC assume MCAR, stronger than MI's MAR.
- However:
  - Arguably,  $MAR \cap MCAR^c$  rare in practice.
  - $\hat{\beta}$  still unbiased for  $\beta$  under CC, AC even under  $MAR \cap MCAR^c$ .
  - In  $MAR \cap MCAR^c$  case, bias does arise if use CC or AC to estimate  $EY$  or  $EX^{(i)}$ . In such case, use Matloff, *Biometrika*, 1982.

# Software

# Software

- Code available at <https://github.com/maxguxiao/Available-Cases.git>.  
Currently under development; check current status.

- Code available at <https://github.com/maxguxiao/Available-Cases.git>.  
Currently under development; check current status.
- R's **cov()**, **cor()** functions include the option **use = 'pairwise.complete.obs'**, which is the AC method.

- Code available at <https://github.com/maxguxiao/Available-Cases.git>.  
Currently under development; check current status.
- R's **cov()**, **cor()** functions include the option **use = 'pairwise.complete.obs'**, which is the AC method. This could be used to implement AC in two applications:

- Code available at <https://github.com/maxguxiao/Available-Cases.git>.  
Currently under development; check current status.
- R's **cov()**, **cor()** functions include the option **use = 'pairwise.complete.obs'**, which is the AC method. This could be used to implement AC in two applications:
  - For PCA, just run **eigen()** on either a covariance or correlation matrix computed for AC as above.

- Code available at <https://github.com/maxguxiao/Available-Cases.git>. Currently under development; check current status.
- R's **cov()**, **cor()** functions include the option **use = 'pairwise.complete.obs'**, which is the AC method. This could be used to implement AC in two applications:
  - For PCA, just run **eigen()** on either a covariance or correlation matrix computed for AC as above.
  - For linear regression, the matrices  $A$  and  $D$  both can be computed using **cov()**, after adjusting via a centering operation.

- Code available at <https://github.com/maxguxiao/Available-Cases.git>. Currently under development; check current status.
- R's **cov()**, **cor()** functions include the option **use = 'pairwise.complete.obs'**, which is the AC method. This could be used to implement AC in two applications:
  - For PCA, just run **eigen()** on either a covariance or correlation matrix computed for AC as above.
  - For linear regression, the matrices  $A$  and  $D$  both can be computed using **cov()**, after adjusting via a centering operation.

# Conclusions

# Conclusions

- Final score: AC had 2 wins, 1 loss.

## Conclusions

- Final score: AC had 2 wins, 1 loss.
- MI quite time-consuming, not recommended unless MCAR an issue.

## Conclusions

- Final score: AC had 2 wins, 1 loss.
- MI quite time-consuming, not recommended unless MCAR an issue.

These slides available at

*<http://heather.cs.ucdavis.edu/SeattleSlides.pdf>*