Session 1165

INTERWEAVING NUMERICAL METHODS TECHNIQUES IN MULTISEMESTER PROJECTS

Dr. Peter Avitabile, Associate Professor
Dr. John Mc Kelliget, Professor
Tracy Van Zandt, Graduate Student
Mechanical Engineering Department
University of Massachusetts Lowell
One University Avenue
Lowell, Massachusetts USA
Peter_Avitabile@uml.edu

Abstract

The numerical processing (integration/differentiation/regression analysis) of data is critical to the reduction/manipulation of experimentally acquired data. Students often take classes in numerical methods as either engineering or mathematics courses. Unfortunately, these courses rarely integrate the material in a meaningful manner such that the students truly appreciate the processing at hand. This being the case, the material is often forgotten as the students "hit the reset button" at the end of the course.

Two projects are discussed which were used in an undergraduate Mechanical Engineering Math Methods course to attempt to circumvent this generic problem. Each project highlights one technique which is particularly vital for later coursework, with the intent of giving students a better idea of its practical application and importance. The projects (one covering numerical integration/differentiation and one covering regression analysis) go beyond the standard textbook coverage of these subjects. Accompanying each project is a MATLAB-based graphical user interface tool which allows the students to further explore and more deeply understand the details of the techniques. This paper presents those projects along with the assessment of the student understanding prior to and following the implementation of the new projects.

I. Introduction

Course material is typically presented in a fashion that compartmentizes concepts within the confines of the course. Students often do not understand how current course material relates to previous or subsequent courses. At the completion of each course, students hit the "reset button" since they see no reason to retain material from the course. Many times the students will then later comment “Why didn’t you tell us that material in supporting foundation classes would be important to completely understand what we’re doing now?” “Why didn’t each course better integrate material together?” “Why didn’t …” and the list goes on and on. Of course, from a professor’s perspective, it is clearly obvious how all the pieces fit together, but the professor’s vantage point is far different than that of the young, inexperienced student. Often, students won’t fully realize the relationship between different approaches until well after the completion of the course—often not until they are working in industry and a problem arises which requires the now “practicing engineer” to “pull all the pieces together”.

In order to improve this situation, students must be given a compelling reason to fully understand and retain the material when it is initially presented. Students learn best with hands-on projects and problems with practical purpose [1]. Without a clear need or a “real problem” to which the techniques can be applied, the theoretical concepts are too abstract and difficult to remember. The concepts taught in foundation courses can too easily become a “blur” to the students—nothing more than a “bunch of words” intermingled with sines, cosines, integrals, Taylor series expansion, etc., with no particular reason or intent.

In the UMASS Lowell Mechanical Engineering curriculum, an effort is being made to try to rectify this by interweaving some of the fundamental STEM material between multiple courses so that students obtain a deeper understanding of important concepts. In particular, it is helpful to integrate the well-defined, theoretical material of foundation classes with the hands-on environment of later laboratory classes. Laboratory can be effectively used to reinforce lecture material that is presented in related courses [2]. It can also be the perfect opportunity for students to address “real problems” that do not follow a prescribed chapter in a text. They must bring to the problem all of their STEM skills to interrogate, decipher and analyze the phenomena observed in the laboratory measurement. Thus the laboratory environment becomes an excellent place for students to “think on their own” since there is definitely “no answer at the back of the book”. Students must be afforded the experience of problems that require them to formulate solutions to problems with no specific straight-line structure to the solution – they must learn how to “think outside the box” [3].

Numerical methods and processing of data is one critical area that needs to be addressed in a fashion that encompasses not only the well-defined analytical methods but also strongly emphasizes the need to process data which is far beyond “well-defined”. The mechanical engineering laboratory exercises used at UMASS Lowell require extensive use of Mathematical Methods techniques. Regression analysis is commonly used, in particular for the calibration of transducers. There is also a set of laboratory exercises that requires the integration and differentiation of displacement and acceleration data. The students have generally had much of this numerical processing of data in an earlier Mathematical Methods for Engineers course. However, the techniques are often presented in that course with neat, clean textbook analytical data, the kind of data that is “never seen in a real measurement environment”. The students never seem to realize that these techniques will be important for solving future problems, and have trouble applying the techniques when they reach the laboratory course.

In order to give more meaning to the material presented in the Numerical Methods course, data sets for integration, differentiation and regression analysis were developed to what they are likely to observe when collecting and processing real measurements in subsequent Mechanical Engineering Laboratory courses. This paper addresses two projects which are given to the students in Numerical Methods which involve regression analysis and integration/differentiation of data.

III Regression Analysis

Regression analysis is performed routinely in the Mechanical Engineering Laboratories exercises. The Numerical Methods course covers this material but often students “go through the motions” of homeworks and tests and receive a grade but really have not firmly grasped the intent of the material. While routine homework and projects are assigned, the data is generally well behaved. The introduction of realistic data forces the students to think more deeply about how regression analysis should be applied to the data.

The students are given a traditional homework assignment to perform a regression analysis on two different sets of data. The first is a non-linear trend with two very distinct regions of linear response. The second is a cubic function that can be approximated as linear over one portion, quadratic over another portion and cubic over the entire range. The data sets are shown in Figure 1 and Figure 2, respectively for the two cases. The students are instructed to perform specific analyses which include hand calculations, MATLAB usage and EXCEL usage to perform the regression analysis to identify the best fit and R^2 value.

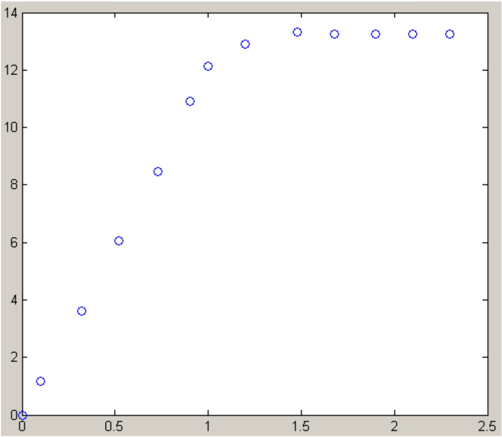


Figure 1 – Data Set for Case 1

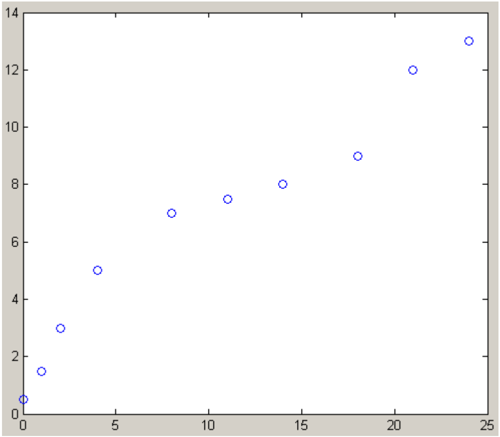


Figure 2 – Data Set for Case 2

As expected, the students generally do only exactly what is requested and do not generally extend the effort beyond that requested. (Since it requires some extra effort by the students, generally additional processing is not explored.) Therefore, some of the “hidden surprises” in these data sets are not well understood or realized.

Following the detailed evaluation of various data sets, the students are presented with a MATLAB Graphical User Interface (GUI) script that enables much easier manipulation of the data. Several data sets are explored where the student can easily manipulate the data and observe. The GUI allows the user to select the data to be used for several “canned” data sets and allows for user defined data to be used. The order of the model can be easily selected for first, second, third and fourth order fit. The R^2 value is reported along with the line describing the data and plotted on the data set used. The GUI allows the student to very easily investigate regression analysis with much more intuitive, immediate feedback.

The first data set is a system which is fairly linear but only over a particular range of the data. The students are requested to find the best fit for the data from the homework but now have much greater flexibility in studying variations from the requested homework info required. Figure 3 shows two possible data fits from the regression analysis where different sets of data points were selected.

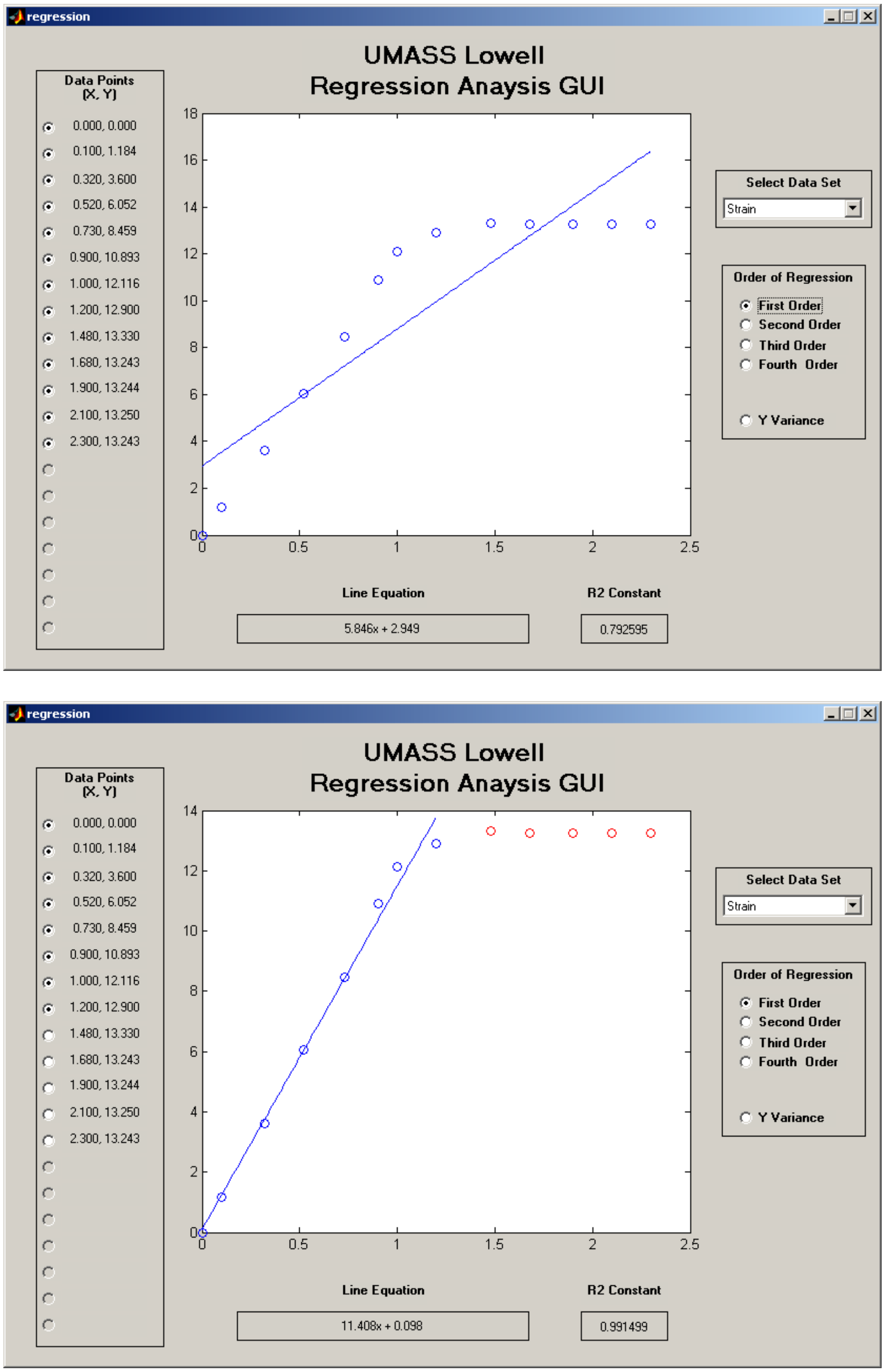
The second data set is a higher order polynomial but can easily be represented over different ranges with either first or second order, or third order over all the data. The original homework only requested the best curve to be fit to the data. However, with the easy manipulation possible with the GUI, students can very quickly assess alternate model order and which particular data points are included in the fit. This GUI allows the students to rapidly make approximations for estimating the function over a variety of different points from the data sets. The student quickly grasps the concepts of regression analysis and the implications of model order and data used with the use of this GUI. Figure 4 shows a variety of different models investigated.

IV Integration & Differentiation (with Contamination)

Integration and differentiation techniques are routinely taught in Numerical Methods courses. Generally, very well behaved data is used for the evaluation of the different techniques employed. However, the laboratory environment is quite different than the “pure” analytical models that are developed. Typically, there are data contaminants related to drift, bias, DC offset and noise which can have a serious effect on the numerically processed data. Students often become very confused when this is the case, since earlier work was well behaved.

Students are presented with a homework problem that considers an object in free fall (constant acceleration) and are requested to numerically integrate to find the displacement of the object (a very routine task). The students are also asked to differentiate and integrate a sine and a cosine wave which have Δt steps specifically chosen to cause some distortion of the differentiated and integrated signal (again another routine task). In both cases, the students generally perform these tasks with ease.

However, a third case involves a set of acceleration data to be integrated that consists of a sine wave with a very, very slight DC offset. Integration of this acceleration signal to provide displacement data causes some confusion and difficulty – unless the student thinks about the combination of the first two cases studied. The general quadratic trend seen in the final result is, of course, understandable due to the offset, but most students fall prey to this problem. While some students quickly see the reality of this problem, many are perplexed by the resulting displacement they have computed. The students fail to think about breaking down the problem into well defined pieces that they already understand to solve the more complicated problems.



Data Points (X, Y)

● 0.000, 0.000
● 0.100, 1.184
● 0.320, 3.600
● 0.520, 6.052
● 0.730, 8.459
● 0.900, 10.893
● 1.000, 12.116
● 1.200, 12.900
● 1.480, 13.330
● 1.680, 13.243
● 1.900, 13.244
● 2.100, 13.250
● 2.300, 13.243
○
○
○
○
○
○
○

Select Data Set: Strain

Order of Regression
● First Order
○ Second Order
○ Third Order
○ Fourth Order
○ Y Variance

Line Equation: 5.846x + 2.949

R2 Constant: 0.792595

Data Points (X, Y)

● 0.000, 0.000
● 0.100, 1.184
● 0.320, 3.600
● 0.520, 6.052
● 0.730, 8.459
● 0.900, 10.893
● 1.000, 12.116
● 1.200, 12.900
○ 1.480, 13.330
○ 1.680, 13.243
○ 1.900, 13.244
○ 2.100, 13.250
○ 2.300, 13.243
○
○
○
○
○
○
○

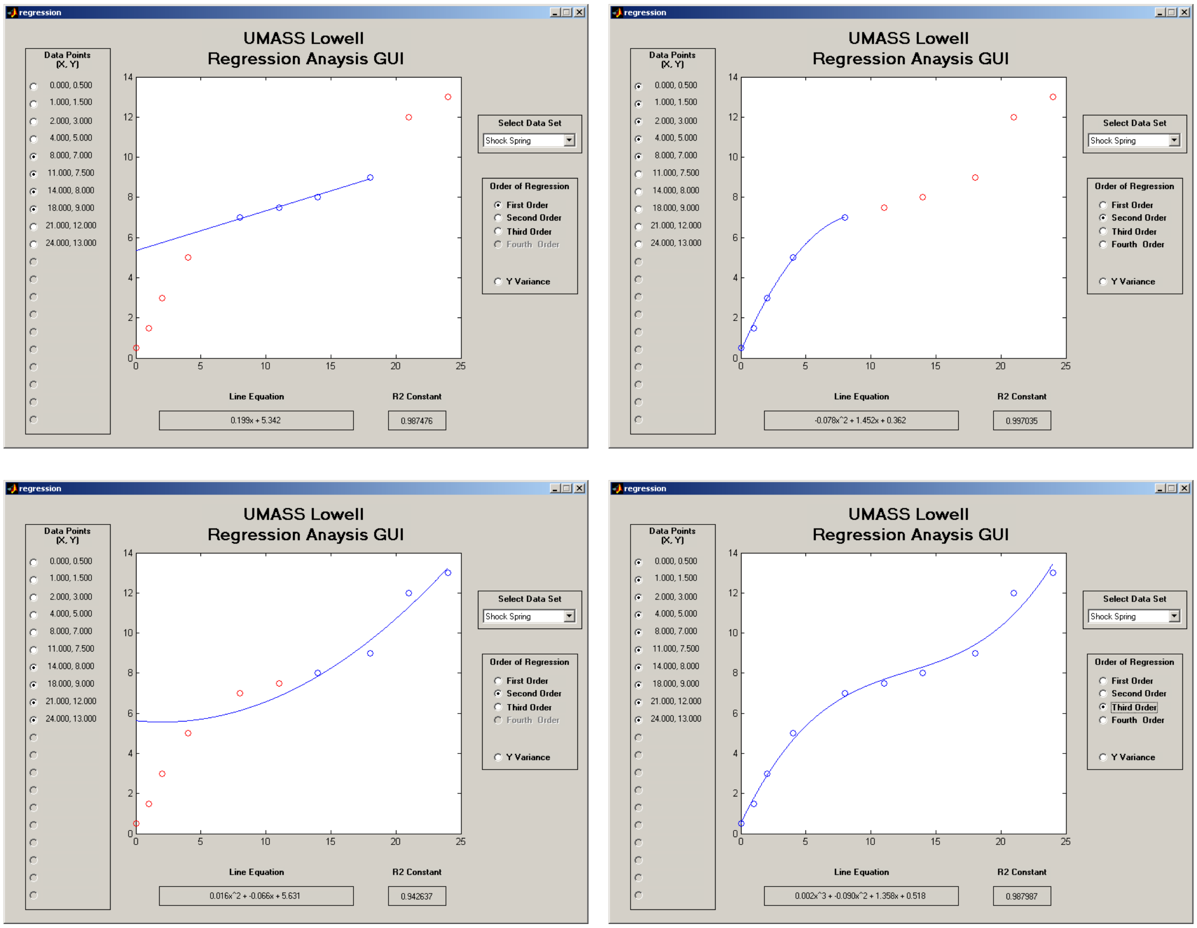
Select Data Set: Strain

Order of Regression
● First Order
○ Second Order
○ Third Order
○ Fourth Order
○ Y Variance

Line Equation: 11.408x + 0.098

R2 Constant: 0.991499

Figure 3 – Linear Regression Analysis – Different Sets of Data Points



Data Points (X, Y): ○ 0.000, 0.500 ○ 1.000, 1.500 ○ 2.000, 3.000 ○ 4.000, 5.000 ● 8.000, 7.000 ● 11.000, 7.500 ● 14.000, 8.000 ● 18.000, 9.000 ○ 21.000, 12.000 ○ 24.000, 13.000
Select Data Set: Shock Spring
Order of Regression: ● First Order ○ Second Order ○ Third Order ○ Fourth Order ○ Y Variance
Line Equation: 0.199x + 5.342
R2 Constant: 0.987476

Data Points (X, Y): ● 0.000, 0.500 ● 1.000, 1.500 ● 2.000, 3.000 ● 4.000, 5.000 ● 8.000, 7.000 ○ 11.000, 7.500 ○ 14.000, 8.000 ○ 18.000, 9.000 ○ 21.000, 12.000 ○ 24.000, 13.000
Select Data Set: Shock Spring
Order of Regression: ○ First Order ● Second Order ○ Third Order ○ Fourth Order ○ Y Variance
Line Equation: -0.078x^2 + 1.452x + 0.362
R2 Constant: 0.997035

Data Points (X, Y): ○ 0.000, 0.500 ○ 1.000, 1.500 ○ 2.000, 3.000 ○ 4.000, 5.000 ○ 8.000, 7.000 ○ 11.000, 7.500 ● 14.000, 8.000 ● 18.000, 9.000 ● 21.000, 12.000 ● 24.000, 13.000
Select Data Set: Shock Spring
Order of Regression: ○ First Order ● Second Order ○ Third Order ○ Fourth Order ○ Y Variance
Line Equation: 0.016x^2 + -0.066x + 5.631
R2 Constant: 0.942637

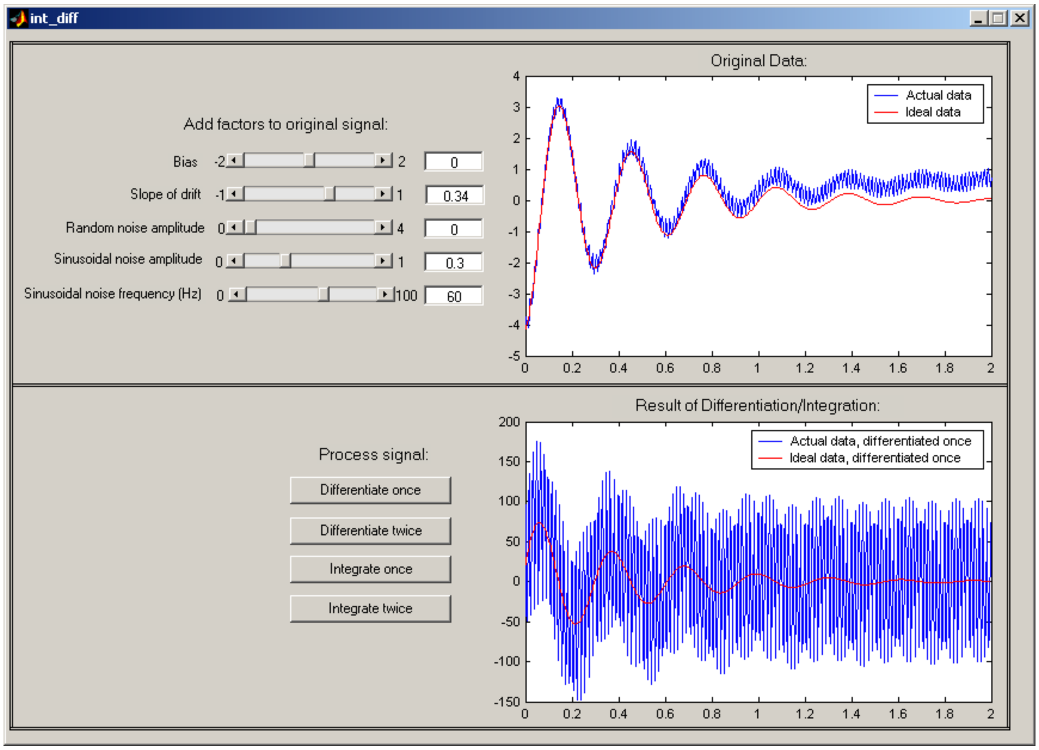
Data Points (X, Y): ● 0.000, 0.500 ● 1.000, 1.500 ● 2.000, 3.000 ● 4.000, 5.000 ● 8.000, 7.000 ● 11.000, 7.500 ● 14.000, 8.000 ● 18.000, 9.000 ● 21.000, 12.000 ● 24.000, 13.000
Select Data Set: Shock Spring
Order of Regression: ○ First Order ○ Second Order ● Third Order ○ Fourth Order ○ Y Variance
Line Equation: 0.002x^3 + -0.090x^2 + 1.358x + 0.518
R2 Constant: 0.987987

Figure 4 – Several Different Model Order Approximations

In order to better illustrate these phenomena, the students are presented with a MATLAB Graphical User Interface (GUI) script that enables much easier manipulation of the data. Several data sets are explored where the student can easily manipulate the data and observe. The GUI allows the user to select various methods to contaminate the data set and then integrate or differentiate the data to observe the resulting phenomena.

Students are required to utilize the GUI to add very specific contaminants to the data – such as drift, bias, offset, 60 cycle noise and random noise. In this very controlled manner, the students can easily see the results of contaminating effects as either differentiation or integration is performed. Figure 5 and Figure 6 show some typical results.

The GUI allows the students to quickly and rapidly observe these effects which present very real laboratory situations that often occur with real data collected. The students better appreciate their basic knowledge of simple effects and how to better apply that knowledge to more complicated data sets.



Add factors to original signal:

Bias -2 2 0

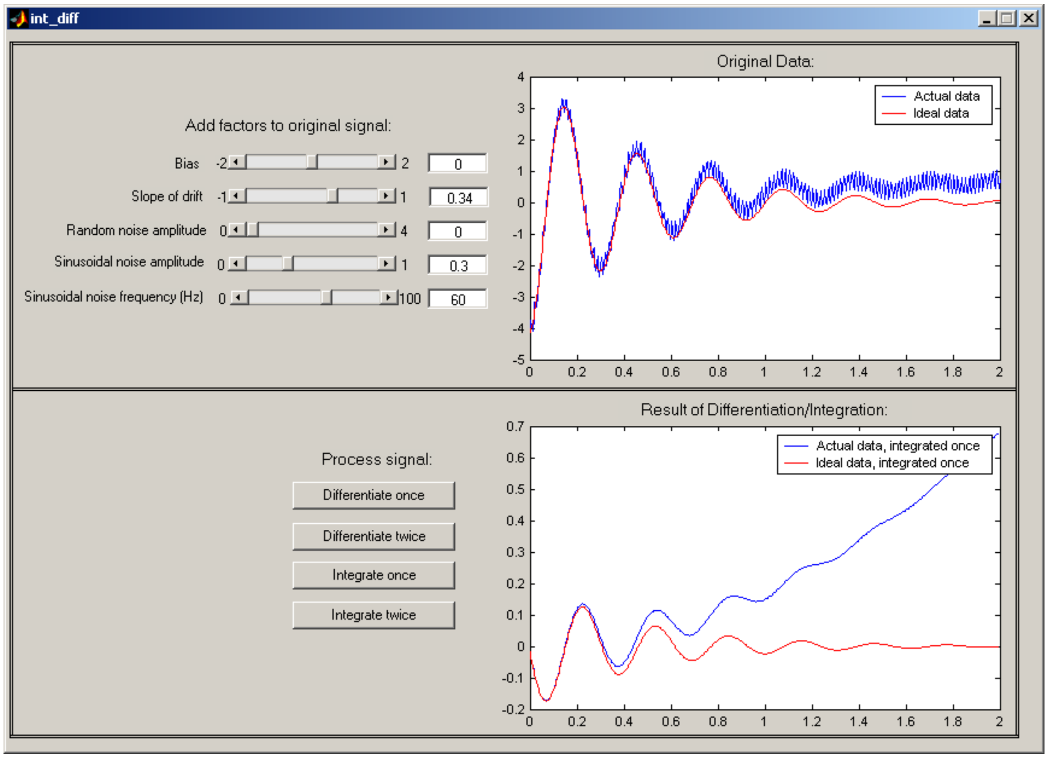
Slope of drift -1 1 0.34

Random noise amplitude 0 4 0

Sinusoidal noise amplitude 0 1 0.3

Sinusoidal noise frequency (Hz) 0 100 60

Figure 5 – Effects of Noise on Differentiation



Add factors to original signal:

Bias -2 2 0

Slope of drift -1 1 0.34

Random noise amplitude 0 4 0

Sinusoidal noise amplitude 0 1 0.3

Sinusoidal noise frequency (Hz) 0 100 60

Figure 6 – Effects of Bias or Drift on Integration

V Summary

In order to help students better understand basic underlying mathematical concepts in numerical methods, two specific projects are described along with MATLAB Graphical User Interfaces (GUI) to complement the project assignment.

One project centers around the regression analysis for several different sets of data that range from linear through cubic order data. Once the assignment is completed, the students are given a MATLAB GUI to further their understanding of regression analysis, order model used as well as data selected. The GUI enables the students to quickly explore alternate solutions and understand the implications of parameters selected in a graphical manner.

The second project focuses on integration and differentiation of waveforms that have been contaminated by various common sources of distortion (noise, bias, drift,etc.). Again the students perform this assignment and then are presented with another MATLAB GUI to enable a more in-depth assessment of these different contaminating effects in a very quick and easy to understand graphical presentation of these effects.

The students generally feel that their overall understanding of the material is enhanced from preliminary ad hoc assessments. However, additional assessments and work with these GUIs is needed to draw more definitive conclusions. This will be addressed in future papers.

VI Acknowledgement

Some of the work presented herein was partially funded by the NSF Engineering Education Division Grant EEC-0314875 entitled “Multi-Semester Interwoven Project for Teaching Basic Core STEM Material Critical for Solving Dynamic Systems Problems”. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation The authors are grateful for the support obtained from NSF to further engineering education.

VII References

1 Davis,B.G., “Tools for Teaching”, Jossey-Bass Publishers, San Francisco, 1993, p100.
2 Piaget,J., “To Understand is to Invent”, Grossman, New York, 1973.
3 Vygotsky,L., “Mind in Society: The Development of Higher Psychological Processes”, Harvard University Press, MA, 1978.
4 Avitabile,P., Hodgkins,J., “Numerical Evaluation of Displacement and Acceleration for a Mass, Spring, Dashpot System”, Proceedings of the American Society of Engineering Education, June 2004, Salt Lake City, Utah

Peter Avitabile is an Associate Professor in the Mechanical Engineering Department and the Director of the Modal Analysis and Controls Laboratory at the University of Massachusetts Lowell. He is a Registered Professional Engineer with a BS, MS and Doctorate in Mechanical Engineering and a member of ASEE, ASME, IES and SEM.

John Mc Kelliget is a Professor and Department Chairman in the Mechanical Engineering Department at the University of Massachusetts Lowell.

Tracy Van Zandt is a Graduate Student in the Mechanical Engineering Department at the University of Massachusetts. She is currently working on her Master's Degree in the Modal Analysis and Controls Laboratory while concurrently working on the NSF Engineering Education Grant.