1-1-2003

A Thermal Time-Constant Experiment

Kyle Ressler
Washington University

Kyle Brucker
Cornell University

Mark L. Nagurka
Marquette University, mark.nagurka@marquette.edu

A Thermal Time-Constant Experiment*

KYLE RESSLER
Dept. of Mechanical Eng., Washington University, St. Louis, MO, USA

KYLE BRUCKER
Dept. of Mechanical Eng., Cornell University, Ithaca, NY, USA

MARK NAGURKA
Dept. of Mechanical & Industrial Eng., Marquette University, Milwaukee, WI, USA.
E-mail: mark.nagurka@marquette.edu

A simple experiment, well suited for an undergraduate course in mechatronics, is described in which thermal time-constant information is extracted from a heater-blower table-top system. In the experiment, a thermistor measures the temperature of a resistive-heater that is cooled by a blower and a microcontroller is used for data acquisition. The student is asked to determine the thermal time response, and in particular the thermal time-constant of the system, for different blower speeds. The experiment prompts questions about modeling a thermal system, and exposes the student to basic concepts of mechatronics including measurement and data analysis.

INTRODUCTION

THIS PAPER describes a thermal time-constant experiment that is reasonably simple, inexpensive, and well suited for undergraduate students. The experiment introduces students to common laboratory mechatronic components and concepts, such as the use of a programmable microcontroller for data acquisition, a thermistor for temperature measurement, and the process of modeling a heater-blower system. The experiment is representative of a practical real-life system, namely, a blower cooling an electrical component that would otherwise reach potentially damaging high temperatures.

The thermal time-constant (TTC) experimental setup is depicted schematically in Fig. 1 and in the photograph of Fig. 2.

The TTC parts list is as follows:

- Parallax BASIC Stamp (BSII) programmable microcontroller
- Parallax 'Board-of-Education™' Board
- Base Plate (25 cm × 15 cm × 5 mm)
- Blower fan (12 V DC, 0.2 A, such as Radio Shack #273-199)
- Relay (12 V DC 0.5 A, such as Newark #PVD1354)
- Resistors (2) (220 Ω)
- Capacitor (2) (0.1 μF)
- Resistive heaters (2) (10 W, such as Radio Shack #271-132)
- Ceramic standoff for heaters (2) (such as, Newark #83F8092)
- Banana clip mounts (2), female (1 red, 1 black)

- Switches (2) (SPST, such as Radio Shack #274-624)
- Blower potentiometer (100 kΩ)
- Thermistor (negative coefficient, such as Radio Shack #271-110A)
- Serial cable
- Laboratory power supply (12 V, 3 A max)
- Windows-based PC

The TTC consists of two resistive-type electrical heaters cooled by a variable speed blower. A resistive-type temperature sensor, a thermistor, is mounted between the heaters, and data acquisition is accomplished using a Parallax BASIC Stamp™ programmable microcontroller. In the experiment, current is supplied to the heaters, causing the temperature to rise above room temperature, and data from the thermistor are collected until steady-state conditions are achieved. The procedure is repeated with the blower operating at different constant speeds, resulting in different temperature profiles. As part of the laboratory exercise the student is directed to transform the resistive data from the thermistor into temperature, and then identify the steady-state temperature and the thermal time-constant of the system at various blower speeds.

The TTC experiment was designed to satisfy multiple objectives. Although from the student's perspective the main objective of the experiment is determining the steady-state temperature and the time-constant of a first-order system, in the process the TTC experiment familiarizes the student with the BASIC Stamp. For example, after understanding features of the BASIC Stamp, the student is asked to open and later modify a prewritten program using the Pbasic editor, and then download it to the Stamp. The experience gained with
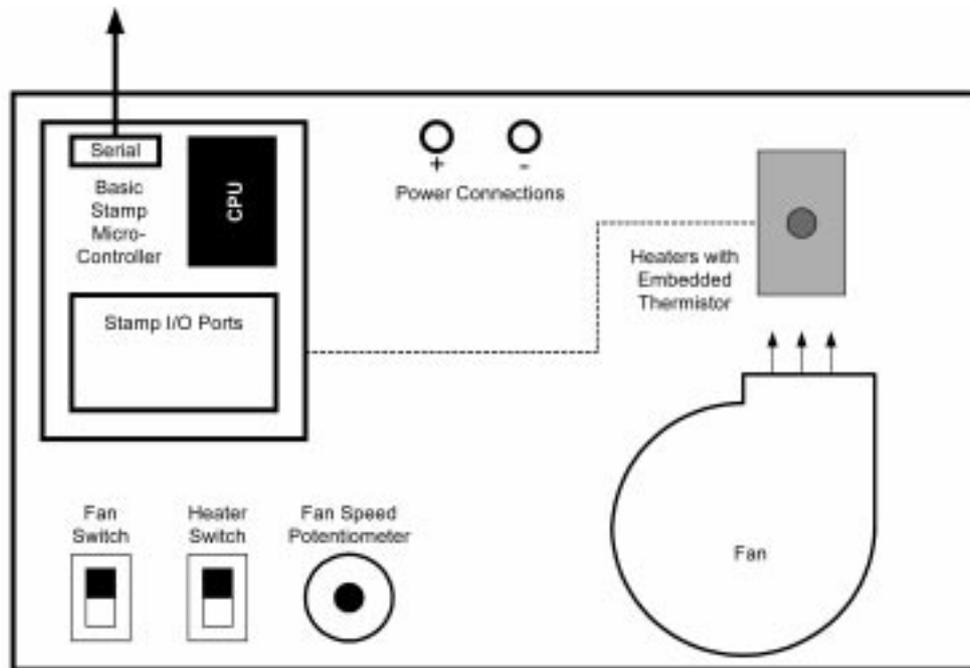
---

* Accepted 6 June 2003.

Fig. 1. Schematic of experimental test-bed.

the BASIC Stamp through this experiment proves valuable for the student in future experiments and projects.

The TTC experiment was intended to be low-cost, repeatable and easy to set up. The experimental test-bed was assembled for under US$50, and the only other requirements are a laboratory power supply, the BASIC Stamp, and a Windows-based PC. Operation of the pre-assembled test-bed (with the BASIC Stamp on a Parallax Board-of-Education™ board) requires that it be serially connected to a Windows-based PC with the necessary software, i.e., the TTC data acquisition program and the PBasic editor, and be connected to a standard laboratory DC power supply (a 12 V, 3 A supply was used). The use of custom-written data acquisition software makes the system simple to operate. Finally, the hardware is easy to store and set up for labs.

REVIEW OF BASIC CONCEPTS

To effectively perform and understand the principles being presented in the TTC experiment it is necessary that the student be familiar with
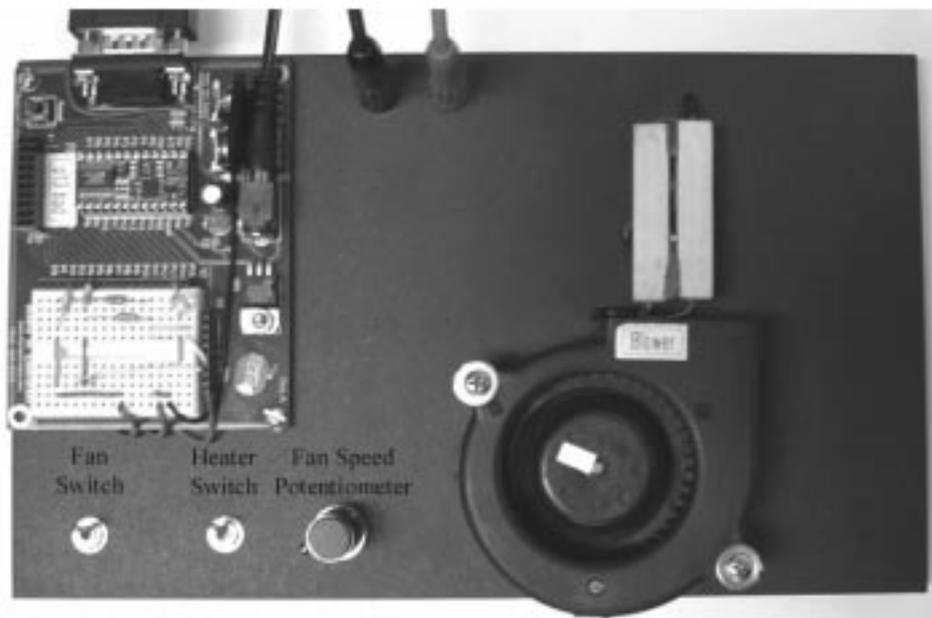

Fig. 2. Photograph of experimental test-bed.

Table 1. Manufacturer's resistance temperature data

Temp (°C)	Resistance (kΩ)
0	27.28
5	22.05
10	17.96
15	14.68
20	12.09
25	10.00
30	8.313
35	6.941
40	5.826
45	4.912
50	4.161
55	3.537
60	3.021
65	2.589
70	2.229
75	1.924
80	1.669
85	1.451
90	1.366
95	1.108
100	0.9375
105	0.8575
110	0.7579

the concepts of 'steady-state temperature' and 'thermal time-constant.'

The steady-state temperature of a first-order thermal system is achieved after the transient response decays to zero and only the steady response remains. During the TTC experiment this condition occurs when an equilibrium temperature is met, i.e., the amount of heat being supplied by the heaters is equal to the amount of heat being dissipated, and thus a steady temperature is maintained. By changing the speed of the blower the amount of heat dissipation can be adjusted giving a different steady-state temperature of the system.

The thermal time-constant provides a measure of the system's rate of response to an input. The time-constant is defined as the time it takes the system to reach 63.2% of the steady-state value relative to its initial value. Since the amount of heat dissipation of the TTC thermal system changes in each run, the time-constant of each run will be different.

OVERVIEW OF EXPERIMENTAL PROCEDURE

Before performing the TTC experiment, the student is asked to complete a prelab assignment. The laboratory manual contains a table of resistance-temperature data for the thermistor, as provided by the manufacturer and presented in Table 1. Prior to coming to lab, the student is asked to determine a second- or third-order best-fit correlation of the data. Figure 3 shows examples of two such fits along with the data.

At the lab station, the student is directed to power the BASIC Stamp on the test-bed, and then open the preprogrammed code with the PBasic editor and download this program to the Stamp. A screenshot of the PBasic editor is presented in Fig. 4. (To simplify the experiment, the downloading step could be conducted prior to students arriving to the laboratory. This was not done in the interest of familiarizing students with the use of programmable microcontrollers.) The student then initializes the TTC data acquisition program to ready the software for data collection.
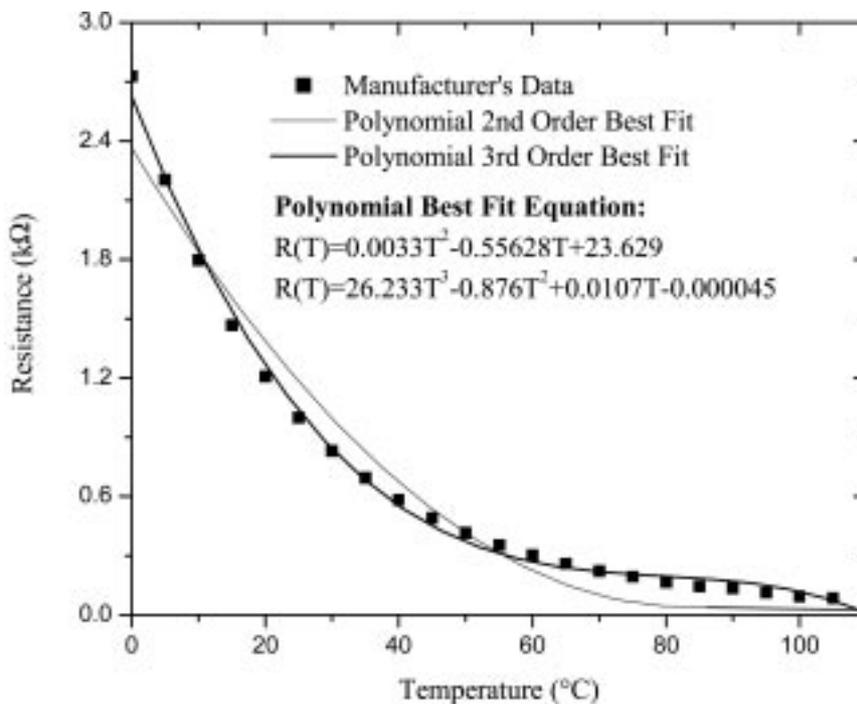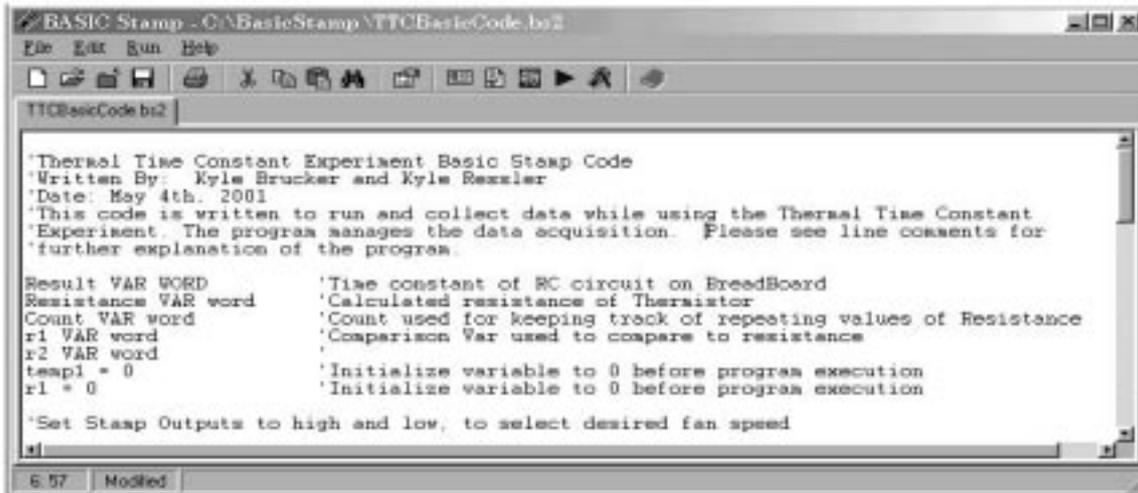

Polynomial Best Fit Equation:
$$R(T) = 0.0033T^2 - 0.55628T + 23.629$$
$$R(T) = 26.233T^3 - 0.876T^2 + 0.0107T - 0.000045$$

Fig. 3. Thermistor resistance-temperature correlation.

Fig. 4. PBasic editor screenshot.

The TTC data acquisition program is a Visual Basic program that was written specifically for this experiment by the authors. A screenshot of this program is shown in Fig. 5. The program serves to set up a text file of the thermistor resistance data readings during the experiment. The file can then be parsed and manipulated using a spreadsheet program or a text editor. The program also serves as a real-time temperature display for the heaters. It could readily be replaced by a commercial data acquisition program.

With the BASIC Stamp configured and the TTC data acquisition initialized, the experiment is ready to be conducted. The blower is left off for the first run. (This can be accomplished by setting the blower potentiometer on the test-bed to its highest resistance.) To run the experiment the 'Start' button on the TTC data acquisition program is

Fig. 5. TTC data acquisition screenshot.

depressed to begin streaming data and the heater switch on the test-bed is turned on. The data are collected and recorded in a text file until steady-state conditions are achieved. (In the program 250 consecutive similar resistance values from the thermistor are used to indicate steady-state conditions have been achieved.) The 'Stop' button on the acquisition screen may be pressed if the user wishes to stop the acquisition manually before steady-state conditions are reached. With the data file for the current case written, the student may proceed to additional runs. The procedure in the laboratory manual asks the student to perform two more runs, each with progressively faster blower speeds.

The analysis of the data starts by associating time values to the acquired resistance values for each case. Although this task could easily be automated within the TTC data acquisition software, it was decided to have the student perform this manually in the interest of reinforcing the concept of sampling rate. In the experiment the BASIC Stamp is set to retrieve values from the thermistor at a rate of one sample per 100 ms. This value can easily be changed within the PBasic code. From the resistance vs. time data and the resistance-temperature correlation, the student can obtain the temperature vs. time history.

In the laboratory manual, the student is asked to create an overlay plot of resistance vs. time and temperature vs. time for the case with the blower off. As presented in Fig. 6, the resistance of the thermistor drops as the temperature increases (since a negative-coefficient thermistor was used). The plot shows the nature of the sensor as the heater temperature increases. The student is then asked to determine how well the data is represented by a first-order model, and then to find the time constant of each of the runs with the blower at different speeds. Figure 7 presents a sample plot of the temperature history for three cases: (i)
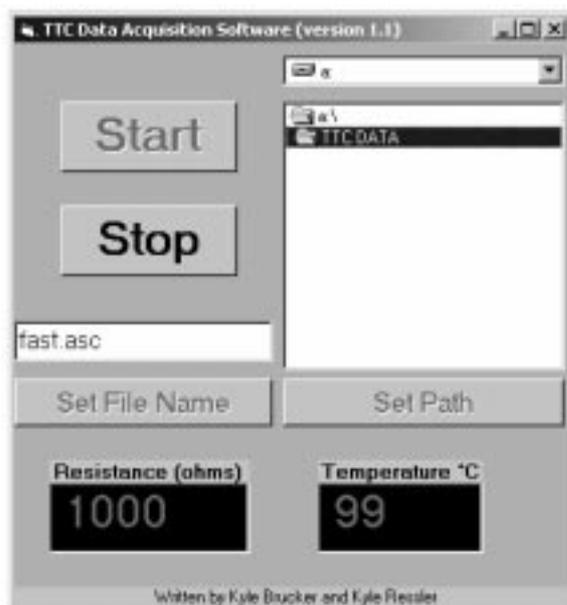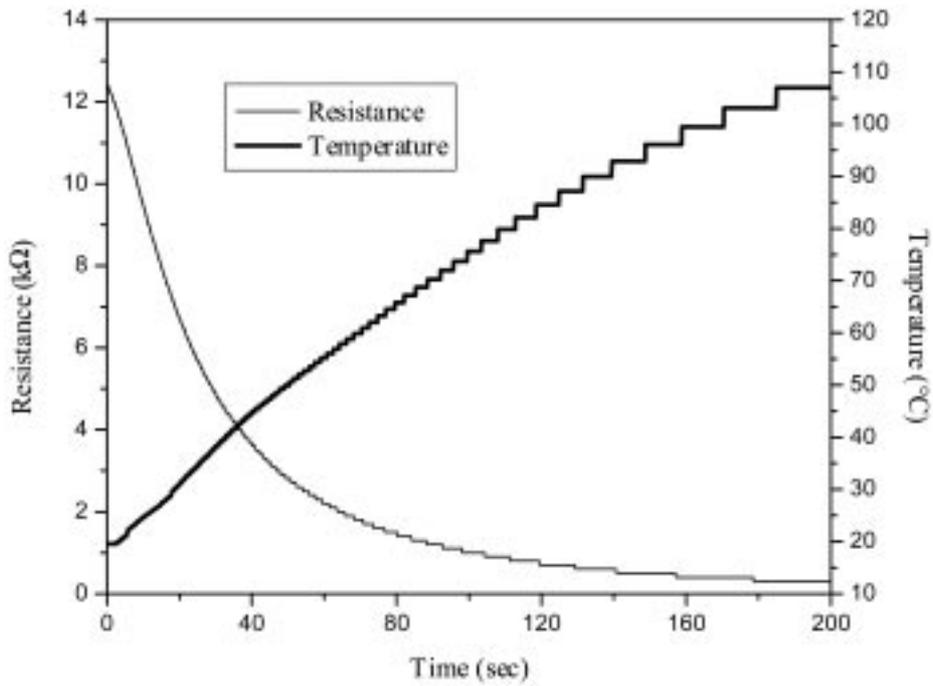
Fig. 6. Overlay plot of resistance and temperature versus time.

blower off, (ii) blower set at a slow speed (1800 rpm), and (iii) blower set at a higher speed (2300 rpm), along with best-fit lines. As convection due to the blower increases, the time-constant and steady-state temperature decrease.

In a final report the student is asked to explain and verify the results developed in the data analysis. Various relevant concepts, such as time-constant and data acquisition, as well as real-world applications are to be emphasized.

DISCUSSION

The TTC experiment provides a comfortable hands-on introduction to core concepts and types of equipment a student may use while studying mechatronics. As an introductory lab, the experiment provides a vehicle to address fundamental issues—such as measurement of a time-constant of a first-order system—associated with a reasonably simple yet real system.
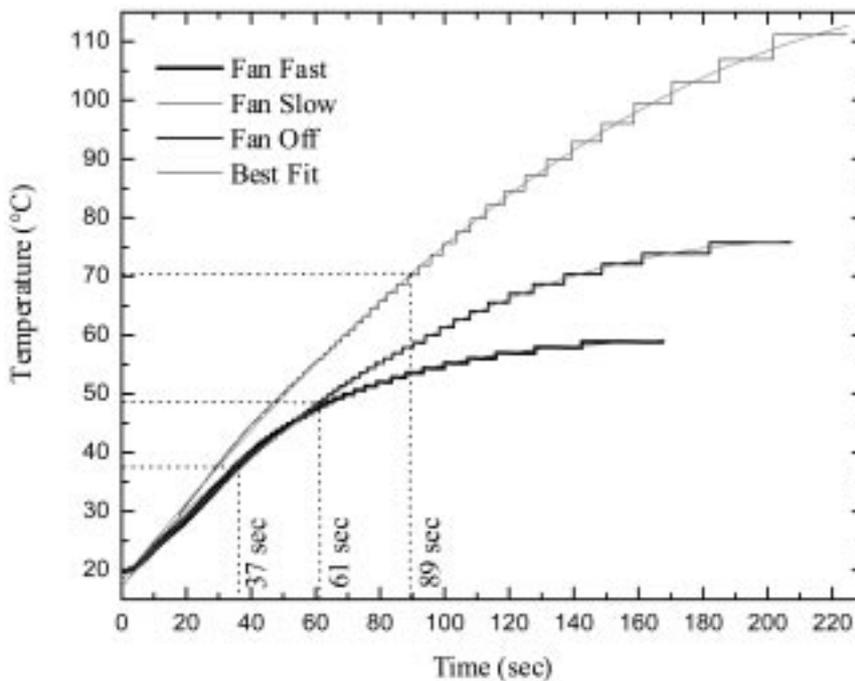

Fig. 7. Temperature versus time for different cases.

Although students generally study the behavior of first-order systems as well as the concepts of steady-state response and the meaning of the term 'time-constant' early in the engineering curriculum, these items often are not experienced in the laboratory. The TTC experiment provides the student the opportunity to investigate a physical system and see the imperfection of actual data compared to a theoretical model. It is also a means to introduce tools of measurement and data acquisition.

It was assumed here that the student was not exposed to or not well versed in the use of data acquisition, an integral part of most engineering labs. For this reason, the experiment relies on a simple stand-alone program with a preset sampling rate. The TTC experiment shows the student what can be done with acquisition and the components used to perform it. The sampling rate was intentionally set a little slow (the cause of the choppiness seen in Figs 6 and 7) to force students to think through the limitations of sampling. It is expected that this topic will be discussed in the laboratory final report. (Students are asked to address the data acquisition methods used and what changes they would make to the setup if they had designed it.) The sampling rate can easily be changed in the lab by manipulating a constant set in the PBasic code.

The experiment demonstrates a problem that is common in today's electronic world, the cooling of electronics. In the final report the student is expected to discuss real-world applications of the principles observed in this experiment. An example would be the control of computer processor chip temperatures.

Extensions

The TTC experiment was designed to be versatile enough for use in subsequent mechatronics experiments. Two future experiments that could easily be adapted from the current setup are (i) advanced data acquisition with sample rate determination and (ii) open-loop and closed-loop control comparisons.

The current version of the TTC experiment utilizes a simple data acquisition program with a predetermined sample rate. A natural extension would be to have the student analyze the system and determine a suitable sample rate. This would allow students to gain experience in selecting the sample rate and test the 'performance' of various rates. A commercial data acquisition program could replace the use of the BASIC Stamp for data acquisition, if desired.

Although this experiment did not actively control the steady-state temperature of the heaters, future experiments are planned where the student would write the PBasic code for the open and closed loop control of the temperature of the heaters via the blower. The addition of an IC potentiometer to the test-bed would be needed to allow for the control of the blower speed with the BASIC Stamp. Using a model of the thermal correlations from the heater-blower system the student could develop an open-loop control algorithm. Then, for comparison, the student could create a closed-loop algorithm based on measurements from the thermistor.

CONCLUSION

The TTC experiment is to be incorporated in the mechanical engineering curricula at Marquette University in two courses: MEEN120: 'Mechanical Measurements and Instrumentation' and in MEEN158: 'Mechatronics'. The hardware requirements for the experiment are minimal: the test-bed (consisting of base plate, blower, resistive heater, thermistor, switch, potentiometer, serial cable, and BASIC Stamp), a DC power supply, and a Windows-based PC computer with a serial I/O connection. The software requirements are minimal, i.e., data acquisition software and the PBASIC editor.

The TTC experimental test-bed was designed to be a simple and versatile piece of laboratory equipment, allowing it to be used 'as-is' and adapted for future mechatronics experiments. The experiment serves as an excellent means of familiarizing students with common laboratory components and processes while minimizing laboratory time and cost.

Kyle Ressler is a Mechanical Engineer at John Deere Horicon Works in Wisconsin. He earned his B.S. degree from Marquette University and his M.S. degree from Washington University in St. Louis, where his research focused primarily on small spacecraft design and observability analysis. His research and publiction of Hybrid Solar Sails recently received high honors at the AIAA/USU Small Satellite Conference.

Kyle Brucker received his B.S. degree in Mechanical Engineering in 2001 from Marquette University where he was inducted into several honor societies (Tau Beta Pi, Pi Tau Sigma, Pi Mu Epsilon, and the National Society of Professional Engineers). He graduated Marquette Cum Laude and received scholastic honors from the College of Engineering.

He is now pursuing a Ph.D. degree at Cornell University. He was recently awarded a National Defense Science and Engineering Graduate Fellowship (NDSEG) to further the investigation of turbulent drag reduction by polymer addition.

Mark Nagurka is an Associate Professor of Mechanical and Biomedical Engineering at Marquette University, where he teaches courses in Dynamics of Mechanical Systems, Mechanical Measurements & Instrumentation, and Mechatronics. He is a dedicated engineering educator, holds a Ph.D. in Mechanical Engineering from M.I.T. and taught previously at Carnegie Mellon University. He is a registered Professional Engineer in Wisconsin and Pennsylvania, a Fellow of the American Society of Mechanical Engineers (ASME), and a former Fulbright Scholar.