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# A MULTIDISCPLINARY CONTROL SYSTEMS LABORATORY

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**Abstract** - The hallmark of the newly configured Rowan College of Engineering undergraduate program is multidisciplinary education with a laboratory emphasis. The development of a new multidisciplinary control laboratory upholds our hallmark very well. We attempt to address the demand of industry for acquiring control engineers (1) with a broad set of skills and a comprehension of the diverse practical applications of control and (2) who can move across rather artificial program boundaries with great ease. Twelve multidisciplinary experiments that integrate hands-on experience and software simulation are investigated. This enables electrical, mechanical and chemical engineering students to learn the fundamental theory and physical implementation of various types of control systems. The first four experiments deal with different first order systems and emphasize their mathematical equivalence. The next two experiments expose the students to Proportional, Integral and Derivative (PID) control using both a DC motor and feedback process control. Performance analyses and the use of instrumentation in control are the fundamentals of the next two experiments. The last four experiments deal with real systems like an engine, helicopter, ball and beam and an anti-lock brake system. Details of an experiment on a first order system are given.

## Introduction

The control systems laboratory is an integrated effort by the Faculty of Engineering at Rowan University to configure a novel hands-on method of teaching Control Systems from a multidisciplinary point of view. The Electrical, Mechanical and Chemical Engineering programs are joining together to achieve this. Although Control is an interdisciplinary technology, there has historically been a tendency for the different engineering departments to teach the subject from their very own somewhat narrow perspective without any semblance of collaboration. This project attempts to address the demand of industry for acquiring control engineers with a broad set of skills and a comprehension of the diverse practical applications of Control [1].

Rowan University began as a teacher education institution. It then evolved into a comprehensive state college and now into a university. The School of Engineering is a recent expansion for the college; a major gift in 1992 from the Rowan Foundation was the catalyst for adding engineering. Our new programs seek to use innovative methods of teaching and learning to prepare students better for entry into a rapidly changing and highly competitive marketplace. Key program features include: (1) multidisciplinary education created through collaborative laboratory and course work; (2) an emphasis on teamwork as the necessary framework for solving complex problems; (3) incorporation of appropriate technologies throughout the curricula; and (4) creation of continuous opportunities for technical communication. To meet these objectives best, our programs include an interdisciplinary *engineering clinic* every semester. Sharing many features in common with the model for medical training, the clinic provides an atmosphere of faculty mentoring in a hands-on, laboratory setting. In addition to the clinic, specialized courses are taught to deliver a well blended combination of theoretical and practical skills. This project is in accordance with the aims of our new programs and strives to meet the requirements of industry in hiring control engineers who can move across rather artificial program boundaries with great ease.

**Goals and Objectives**

Our aim is to accomplish the following:

1. Give students an exposure to the different aspects of control theory in the form of multidisciplinary laboratory experiences that include electrical, mechanical, fluid and thermal systems. In fact, the underlying theory of each of these systems can be explained using circuit theory as these four systems can be modeled as an equivalent circuit [2].
2. Ensure that our laboratory has an impact on a wide variety of courses in our curriculum including the interdisciplinary clinic sequence and core courses in each engineering program.
3. Since digital technology is predominant in today's industry, students should be exposed to data acquisition and digital control for multidisciplinary purposes.
4. Integrate software simulation with hands-on laboratory work using MATLAB, its associated SIMULINK package and C++ programming.

5. Expand student teamwork experience by making group projects an integral part of the course structure.
6. Continue to improve written and oral communication skills of our students.

**Description of Curriculum and Experiments**

Control education must integrate theory, hands-on experience and software simulation in a well balanced fashion [1-8]. The laboratory will have a major impact on the control courses offered by the Electrical, Mechanical and Chemical engineering departments and on other courses in the curriculum that include the Engineering clinic, Fluid Mechanics, Mathematics for Engineering Analysis, Digital Signal Processing and Digital Systems and Microprocessors. The courses generally have three hours of laboratory per week in addition to two to three hours of lectures.

The curriculum in the control courses offered by the departments include:

1. Basic system concepts: linearity, time-invariance, stability, frequency response, causality, realizability and transfer function (poles and zeros).
2. Mathematical modeling of physical systems: analogs between electrical, mechanical, fluid and thermal systems and their circuit equivalence; differential equation description of such systems and their analysis; block diagram algebra; signal flow graphs.
3. Feedback: open loop and closed loop systems; pole placement; compensator design; proportional-integral-derivative (PID) controllers.
4. Stability Analysis: Routh-Hurwitz criterion; root locus method; Nyquist criterion.
5. Frequency response analysis: Bode plots; gain and phase margins.

The basic differences in the lecture content of the courses lies in the emphasis on certain topics and applications by the different departments. Electrical engineering students may see more examples on circuits in the classroom while chemical engineers will see more examples on process control. In the laboratory (common to all students), students will be exposed to a broad range of applications of control theory. This will reinforce analogies between different types of systems. It is these experiments which are summarized below.

The first four experiments deal with different first order systems and emphasize their mathematical equivalence. Different control concepts are taught using a resistor-capacitor (RC) circuit, a mass damper system and the Level/Flow Process Control System. The next two experiments expose the students to Proportional, Integral and Derivative (PID) control using both a DC motor and feedback process control. Performance analyses and the use of instrumentation in control are the fundamentals of the next two experiments. The last four experiments deal with real systems like an engine, helicopter, ball and beam and an anti-lock brake system. Software is integrated with the experiments. The packages of MATLAB and SIMULINK will be used. In addition, real-time process monitoring in a Windows environment with data acquisition will be taught. Digital control will be part of some of the experiments.

Experiment 1 Time domain characteristics of first order systems: The equivalence of a resistor-capacitor (RC) circuit, a mass-damper system, a fluid system with a pressure source leading water to a fill up a tank, and the DC motor of a mechanical servo unit is established. A common transfer function is derived and the concept of a time constant is introduced. The SIMULINK software is used to observe the outputs for various inputs notably a step input. The actual responses of these systems are measured for a step input. This is compared to what is obtained using SIMULINK.

Experiment 2 Process modeling and disturbance impact of first order system: The Level/Flow Process Control System is used to study process modeling and dynamic response. Although this is a second order system, it can be easily converted to a first order system. The system is used to investigate the dynamic response of an open loop, first order system to a disturbance in inlet or outlet flow rate. By performing parametric studies and comparing the dynamic response with that predicted by their model, students get a feel for the importance of the open loop time constant and the process gain. By modifying the system to include two chemical components (for example, a dye and water), an additional variable is introduced (concentration of the dye). The process tank is described by two first order differential equations, one of which has a nonlinear term. Students have to linearize their model and compare their predictions with the actual dynamic response.

Experiment 3 Frequency domain characteristics and digital counterpart of first order systems: Since system equivalence is established, the RC circuit is used as the model. The frequency response of the circuit is measured by using sinusoids at various frequencies as the input. A Bode plot is derived from which the – 3 dB bandwidth, gain margin and phase margins are calculated. A more complex square wave is now an input to the circuit. A spectrum analyzer is used to observe the spectra of the input and output and the results are explained using Fourier analysis. The first order system is converted to a discrete time system using the bilinear transformation [9] for various sampling rates. A C++ code is written to achieve the bilinear transformation. The frequency response of the discrete system is obtained using MATLAB and the effects of sampling rates are studied.

Experiment 4 Sensitivity of a first order system: Students derive the sensitivity of the transfer function with respect to parameters R (resistor) and C (capacitor) and plot the frequency response of the sensitivity. The values of R and C are changed (one at a time) and the sensitivity results are experimentally verified. A real audio signal serves as the input to the system. The input and output spectra are analyzed for various values of R and C to better comprehend the filtering effect.

Experiment 5 Proportional, Integral and Derivative (PID) control: Students first demonstrate the realization of a PID controller using operational amplifiers [2,10,11]. Students then design their own PID controller to control the position of the DC motor of the mechanical servo unit. The design of the controller is equivalent to setting the gain parameters to get a desired output response, achieve a low steady-state error and ensure that the system is stable. The theory on system response, error and stability are applied to a practical problem. In addition, the root locus of the system is derived and verified using MATLAB. From the root locus plot, various gain settings are imposed to verify stability, marginal stability and instability. Based on the analog controller, a digital controller is designed for position control of the DC motor (the digital servo control unit is used). Again, system response, steady-state error and stability are analyzed. The root locus plot is again done and compared to the plot for the analog controller.

Experiment 6 PID Feedback Process Control: The Level/Flow Process Control System will be used to study basic characteristics of Proportional (P) and Proportional-Integral-Derivative (PID) control. Students observe the effect of controller gain on steady state offset using P control and investigate the effect of controller parameters on the dynamic response of the system for PID control. By using P control and PID control of both level and flowrate, students investigate the importance of both the process parameters and the controller parameters to the dynamic response of the closed loop system. Students model the system, derive transfer functions, and determine the closed loop time constant and the damping coefficient (with PID control).

Experiment 7 Performance Criteria and Controller Tuning: The system is used to provide hands-on experience with an on-line tuning method (the Ziegler-Nichols procedure [12]). An automatic tuning method is also used, and students compare the closed loop performances of the system using standard performance criteria (peak overshoot ratio and decay ratio).

Experiment 8 Instrumentation: Students analyze the components of the basic feedback control loop. Students practice transmitter and controller calibration. The characteristics of a linear valve are investigated via calibration of a linear gate valve for flow control as described in [13]. The Feedback Level/Flow Control System uses a potentiometer float type level sensor. Students introduce a pressure transducer into the control loop and calibrate it as a liquid level indicator.

Experiment 9 Engine Speed Control: This experiment, consisting of a scaled model of an engine, is designed to study dynamical systems and control engineering using either analog or digital control. This particular experiment demonstrates the problems encountered in regulating the speed of rotating machinery. In particular, it demonstrates the problems associated with nonlinear control systems [14,15]. The primary objective is to regulate the engine speed by manipulating the position of the motorized valve. This experiment is also designed to illustrate nonlinearity compensation using dither signals, multiple loop/minor loop feedback, system modeling from step response information, (PI) control and root locus methods.

Experiment 10 Helicopter Model: A two-degree of freedom helicopter model is used in this experiment to study advanced control investigations including controller design, state feedback, decoupling techniques and robust controllers. The proposed experiment consists of a model helicopter mounted on a pivot support with two degrees of freedom. This experiment allows direct derivation of a general mathematical model of a helicopter using Lagrange equations, linearization and simplification. A wide variety of experiments including on-line identification of parameters of a linear model, closed-loop response analysis, system decoupling techniques, diagonalization of a system transfer matrix, state space methods, state feedback design and other robust controller designs [16,17] are performed.

Experiment 11 Ball and Beam: This experiment demonstrates the control problems associated with unstable systems. Examples of such systems include a missile during launch. Active control is required to prevent the missile from going unstable and toppling over. In this experiment a steel ball is free to roll on two parallel tensioned wires. These wires are mounted on a beam, pivoted at its center, such that the beam angle may be controlled by a servo motor and sensed by transducers to provide signal outputs of both the beam angle and ball position. The basic control problems is to regulate the ball position by varying the beam angle. This system is naturally unstable, being essentially a double integrator, and consequently requires active feedback control using phase advance methods. The experiments that will be performed include the measurement of system dynamics by transient and closed loop methods, design of analog phase advance compensators and the design of state reconstructors to obtain estimates of ball velocity and position.

Experiment 12 Automotive Mechatronics Control Systems: Students are also introduced to real world systems such as an Anti-lock Brake System. Here the students have to understand the function of each sub-system, namely, the mechanical, hydraulic, electrical/electronic, computer hardware and software, and then, perform an analysis. This involves disconnecting these systems from the existing proprietary microprocessor control systems [3,4,18] and interfacing them with personal computers. Once completed, students conduct an in-depth study of these systems, identifying their elements and conducting experiments on their performance under different conditions by reprogramming. Initiatives are also underway to incorporate smart steering system and fuzzy engine knock control into the mechatronics [19,20] laboratory at Rowan.

**Details of Experiment on First Order Systems**

We have just started to implement the experiments described above. Some details on experiments 3 and 4 are now given. Students build a first order lowpass filter [11] as shown in Figure 1. The component values are $R_1 = R_2 = 1000$ ohms and $C = 0.47$ microfarads. This results in a cutoff frequency of 338.63 Hz. The transfer function T(s) (Laplace transform domain) is derived along with an expression for the magnitude of the frequency response. This is experimentally verified by using sinusoids at various frequencies as the input and measuring the magnitude of the output. The magnitude of the frequency response is also obtained using MATLAB. The transfer function of the filter is

$$T(s) = \frac{-R_2}{R_1(R_2 C s + 1)}$$

The magnitude of the frequency response is shown in Figure 2. To understand the filtering effect, a sum of sinusoids at frequencies in both the passband and stopband are applied as input. A spectrum analyzer is used to observe and explain the response at both the input and output. This is repeated for a squarewave.

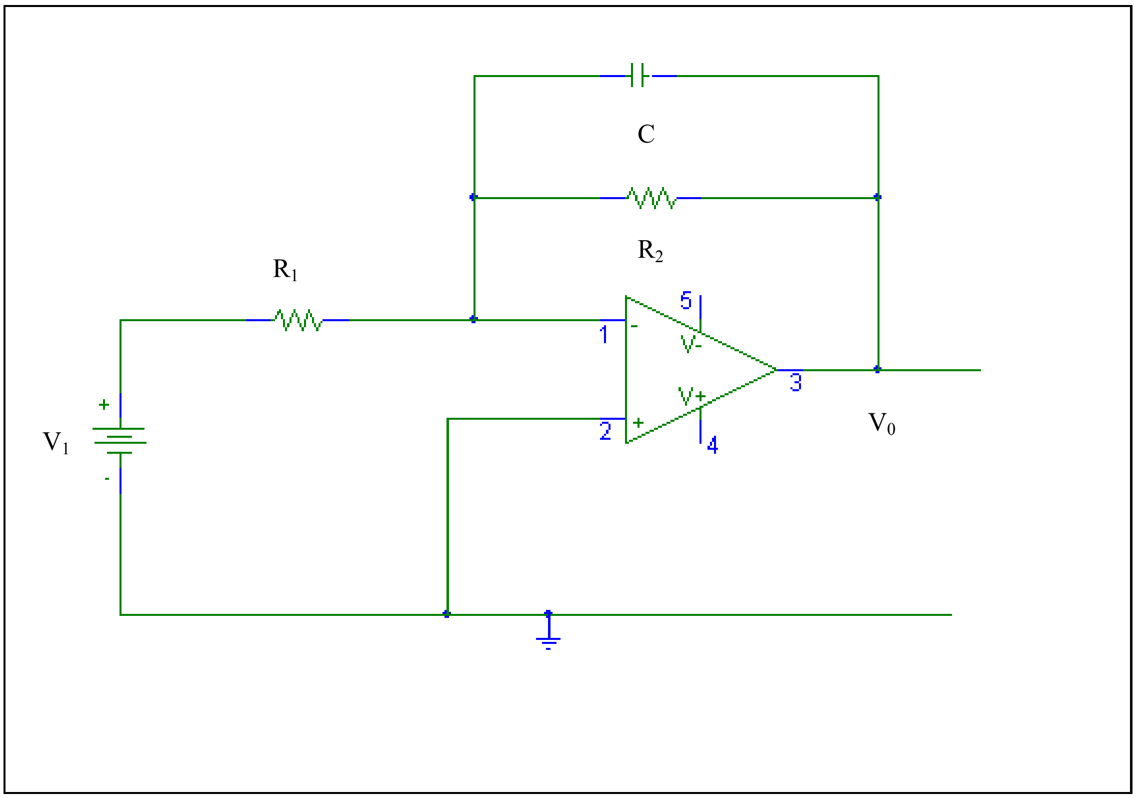


**Figure 1** Circuit diagram of first order lowpass filter

Students derive the sensitivity S of the transfer function [2] to both resistors and the capacitor and plot the magnitude of the frequency response of the sensitivity. The sensitivity of the transfer function T to a parameter k is defined to be the ratio of the proportional or percentage change in T to the proportional or percentage change in k [2]. The general formula for the sensitivity is

$$S_k^T = \frac{\partial T / T}{\partial k / k} = \frac{\partial T}{\partial k}\frac{k}{T}$$

The results for the lowpass filter are:

$$S_{R_1}^T = \frac{\partial T}{\partial R_1}\frac{R_1}{T} = -1$$

$$S_{R_2}^T = \frac{\partial T}{\partial R_2}\frac{R_2}{T} = \frac{1}{R_2 C s + 1}$$

$$S_C^T = \frac{\partial T}{\partial C}\frac{C}{T} = \frac{-R_2 C s}{R_2 C s + 1}$$

Students start with the initial resistor and capacitor values and introduce a change (one component at a time) to verify the sensitivity formulas experimentally. First $R_1$ is changed from 1000 to 1100 ohms (increase by a factor of 10 percent). Since the corresponding sensitivity is –1 for all frequencies, T decreases by a factor of 10 percent at all frequencies.

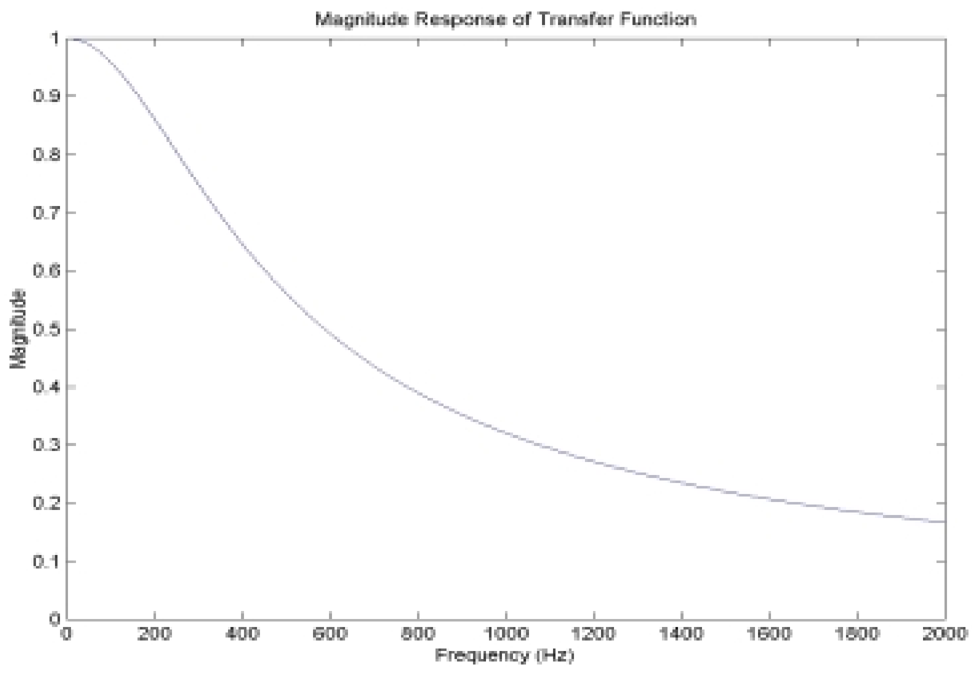


**Figure 2** Magnitude response of transfer function

The sensitivity with respect to $R_2$ is lowpass in nature and hence, a change in $R_2$ has more impact at low frequencies. Students change $R_2$ from 1000 to 1100 ohms (increase by a factor of 10 percent) and measure how the transfer function changes with frequency. At a low frequency of 10 Hz, the sensitivity is about 1 and hence, T like $R_2$ increases by a factor of 10 percent (from 1 to 1.1). At a high frequency of 2000 Hz, the calculations require more explanation and involve complex numbers. Let i denote the complex number where $i^2 = -1$. The proportional change in $R_2$ is (1100-1000)/1000 = 0.1. When $R_2$ = 1000, T = -0.027868 + 0.1646 i. When $R_2$ = 1100, T = -0.025458 + 0.1654 i. The proportional change in T is:

[ (-0.025458 + 0.1654 i) – ( -0.027868 + 0.1646 i) ] / (-0.027868 + 0.1646 i) = 0.0023 – 0.0150 i

The sensitivity is found to be (0.0023 – 0.0150 i) / 0.1 = 0.023 – 0.150 i. Evaluating the sensitivity function given above at 2000 Hz gives 0.028 – 0.165 i. The experimental and actual values are close.

The sensitivity with respect to C is highpass in nature and hence, a change in C has more impact at high frequencies where the sensitivity is close to -1. Students change C from 0.47 microfarads to 1 microfarad and measure how the transfer function changes with frequency. The proportional change in C is (1-0.47)/0.47 = 1.1277. At a low frequency of 80 Hz and when C = 0.47 microfarad, T = -0.94714 + 0.22376 i. When C = 1 microfarad, T = -0.7983 + 0.40127 i. The proportional change in T is:

[ (-0.7983 + 0.40127 i) – ( -0.94714 + 0.22376 i) ] / (-0.94714 + 0.22376 i) = -0.1069 – 0.21267i

The sensitivity is found to be (-0.1069 – 0.21267 i) / 1.1277 = -0.0948 – 0.1886 i. Evaluating the sensitivity function given above at 80 Hz gives -0.0529 – 0.2238i. The experimental and actual values are not as close as for $R_2$ since a relatively bigger change was introduced for C. The sensitivity formulae are more accurate for small parameter changes. Figure 3 shows the plot of the magnitude of the sensitivity of T with respect to C.

## Summary

This NSF-funded project has just commenced at Rowan. We have described twelve multidisciplinary control experiments and given details on an experiment relating to parameter sensitivity of a first order system. The experiment allows the students to gain a better grasp of the concept of sensitivity by actually changing circuit components and seeing the impact on the transfer function.

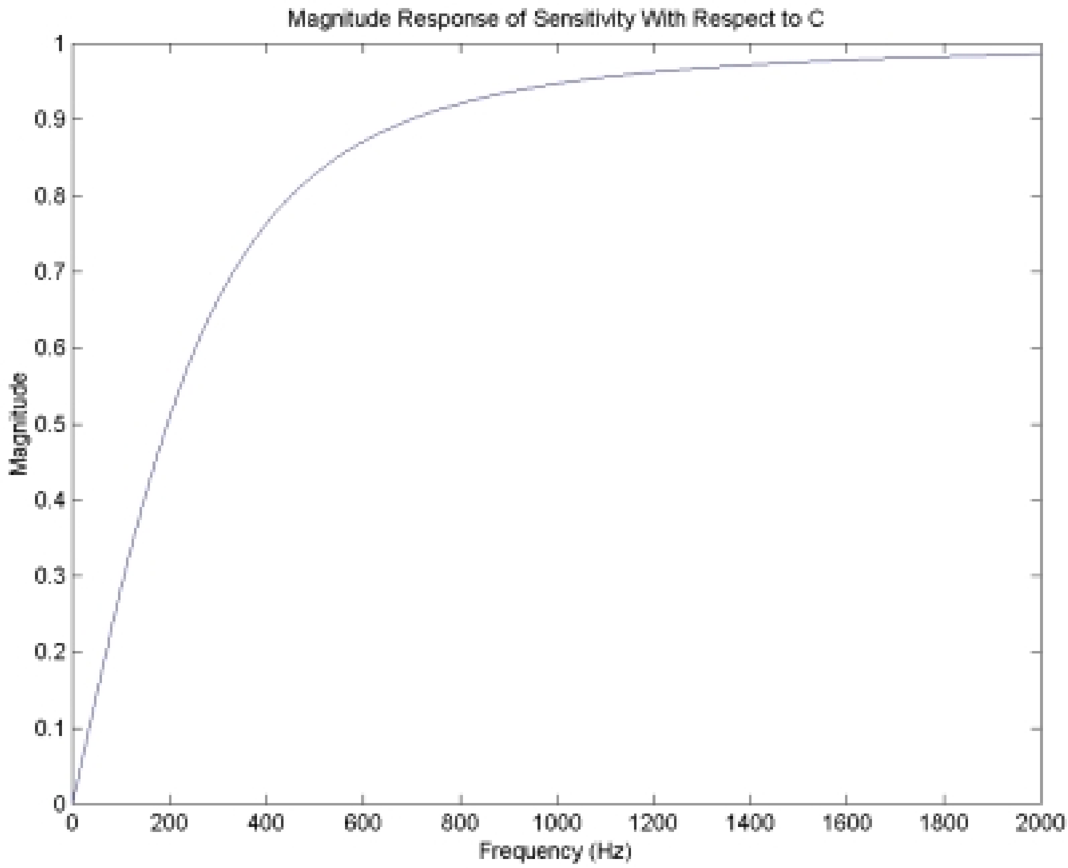


**Figure 3** Magnitude response of sensitivity with respect to C

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## Biography

Ravi P. Ramachandran is an Associate Professor in the Department of Electrical and Computer Engineering at Rowan University. He received his Ph.D. from McGill University in 1990 and has worked at AT&T Bell Laboratories and Rutgers University prior to joining Rowan.

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