Robotics and Prosthetics at Cleveland State University: Modern Information, Communication, and Modeling Technologies

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Abstract. This chapter concentrates on the correlation between research-based education, government priorities and research funding. Special attention is paid to an analysis of the role of modern information and communication technology (ICT) in the education of engineering students. Successful cases with specific description of computer modeling methods for the implementation of prosthesis and robotics research projects are presented based on experiences in the Embedded Control Systems Research Laboratory of Cleveland State University.

Keywords: Robotics · Prosthetics · Modeling · Research-based education

1 Introduction

Information and communication technologies (ICT), mathematical modeling, and computer simulation play a significant role in higher education. Most advanced educational systems in the world are oriented toward the implementation of educational processes of modern ICT and software for modelling and simulation in various fields of human activity, including science, engineering, and technology. This approach is required for the efficient training of students at various levels: undergraduates, graduates, and doctoral students. Many international conferences on ICT and its applications for education are devoted to the use of computer modeling, open-source software, pedagogical e-learning, web-based e-learning, course-centered knowledge management and application in online learning based on web ontology, on-online learning in enterprise education, simulation languages, modeling and simulation for education and training, improving education through data mining, 3D software systems, 3D visualization, wireless communication, experimental teaching of program design, different approaches in teaching programming, web-based computer-assisted language learning, and so on.

A. Ginige et al. (Eds.): ICTERI 2016, CCIS 783, pp. 133–155, 2017.
https://doi.org/10.1007/978-3-319-69965-3_8

It is important that university and IT-industry participants of conferences try to find efficient solutions for the abovementioned computer-modeling-based educational problems. For example, participants from 178 different academic institutions, including many from the top 50 world-ranked institutions, and from many leading IT corporations, including Microsoft, Google, Oracle, Amazon, Yahoo, Samsung, IBM, Apple, and others, attended the 12th International Conference on Modeling, Simulation and Visualization Methods, MSV-2015, in Las Vegas, Nevada, USA.

If IT industry today supports higher education, then tomorrow's IT-based companies, government research agencies, and national laboratories will obtain the high-quality graduates that they need. New achievements in ICT require continuous tracking by educators, and implementation in education.

Successful introduction of ICT to higher education based on research-oriented education and training is considered and analyzed in this chapter. The focus is on the role of computer modeling and simulation in prosthesis and robotics research for increasing student quality, including grading their practical skills, and including efficient professor-student interactions.

This chapter is organized as follows. Section 2 reviews related literature and discusses the challenge of integrating research and education. Section 3 summarizes research-based education at Cleveland State University (CSU). Section 4 summarizes seven research-based education projects at CSU. Section 5 briefly discusses the common training, skills, and educational program at CSU that enables the success of research-based education. Section 6 concludes the chapter.

2 Related Works and Problem Statement

Many publications are devoted to teaching methods and approaches based on ICT and computer modelling, for increasing the efficiency of their interrelation: qualitative modeling in education [3], computer simulation technologies and their effect on learning [24], opportunities and challenges for computer modeling and simulation in science education [34], web-based curricula [4] and remote access laboratories, computer-based programming environments as modelling tools in education and the peculiarities of textual and graphical programming languages [17], interrelations between computer modeling tools, expert models, and modeling processes [44], efficient science education based on models and modelling [9], educational software for collective thinking and testing hypotheses in computer science [26], and others.

A lot of publications deal with improving teaching efficiency for specific courses by introducing modern ICT and computer modelling technologies. In particular, modelling supported course programs, computer-based modelling (AutoCAD, Excel, VBA, etc.) and computer system support for higher education in engineering [8]; software to enhance power engineering education [35]; computer modeling for enhancing instruction in electric machinery [23]; computer modelling in mathematics education [40]; GUI-based computer modelling and design platforms to promote interactive learning in fiber optic communications [45]; RP-aided computer modelling for architectural education [36]; teaching environmental modelling; computer modelling and simulation in power electronics education [27]; and a virtual laboratory for a communication and computer networking course [22].

Special attention in the literature [5, 15, 16] is paid to the role of ICT and modeling technology in education and training in the framework of research-based curricula. This educational approach deals first with educational directions such as robotics, mechatronics, and biomechanics (RMBM) [12, 33, 41]. The correlation of RMBM with ICT and modeling are underlined by results such as: a multidisciplinary model for robotics in engineering education; integration of mechatronics design into the teaching of modeling; modelling of physical systems for the design and control of mechatronic systems [41]; biomechanical applications of computers in engineering education [33]; computerized bio-skills system for surgical skills training in knee replacement [6]; computer modelling and simulation of human movement [25]; computer modelling of the human hand [19]; and design and control of a prosthesis test robot [29, 30].

This chapter builds upon, and extends, the references discussed above. The basic classroom teaching methods, approaches, and specific courses at CSU are similar to those at universities across the world. However, those characteristics are not the primary determinants of research-based education. This chapter presents the features of research-based education at CSU by reviewing seven specific graduate student-led research projects. As the research projects are discussed in the following sections, the reader will note their commonalities, including common tools, research approaches, motivation, and societal focus. The main aims of this chapter are given as follows.

(a) Description and analysis of research-based education based on the experience in the Embedded Control Systems Research Laboratory at the Electrical Engineering and Computer Science Department at the Washkewicz College of Engineering at Cleveland State University (CSU), USA, with a focus on undergraduate, graduate, and doctoral student participation in prosthesis and robotics research, which is funded by the US National Science Foundation (NSF);
(b) Analysis of applied ICT and modeling technologies and advanced software, as well as their implementation in student research, including course work, diploma projects, and Doctoral, Master's, and Bachelor's theses;
(c) Focus on the correlation between student research and government science priorities based on successful cases of ICT and advanced modelling implementation in US government-funded prosthesis research, with particular focus on undergraduate, graduate, and doctoral student participation in prosthesis and robotics research.

3 Research-Based Education and Government Priority Project

CSU's research project "Optimal prosthesis design with energy regeneration" (OPDER) is funded by the US NSF (1.5 M USD). Professors and students from the Department of Electrical Engineering and Computer Science, and the Department of Mechanical Engineering, are involved in research according to the project goals, which deal with the development of: (a) new approaches for the simulation of human limb control; (b) new approaches for optimizing prosthetic limb control, capturing energy during walking, and storing that energy to lengthen useful prosthesis life; (c) prosthesis prototype development.

The human leg transfers energy between the knee, which absorbs energy, and the ankle, which produces energy. The prosthesis that results from this research will mimic the energy transfer of the human leg. Current prostheses do not restore normal gait, and this contributes to degenerative joint disease in amputees. This research will develop new design approaches that will allow prostheses to perform more robustly, closer to natural human gait, and last longer between battery charges.

This project forms a framework for research-based education. Doctoral, graduate, and undergraduate students are involved in research such as: the study of able-bodied gait and amputee gait; the development of models for human motion control to provide a foundation for artificial limb control; the development of electronic prosthesis controls; the development of new approaches for optimizing prosthesis design parameters based on computer intelligence; the fabrication of a prosthesis prototype and its test in a robotic system; the conduct of human trials of the prosthesis prototype.

The role of student participation in all aspects of the research is significant for increasing their qualifications for their careers, for presentations at conferences, for publishing in journals, and for research with professors who can help them be more successful in building their future careers in industry or academia. In the next section we describe the student contribution to prosthesis and robotics research at CSU.

4 Student Contributions to Prosthesis and Robotics Research

Successful cases of student research in the framework of the OPDER project are described in this section.

Evolutionary Optimization of User Intent Recognition (UIR) for Transfemoral Amputees. Powered prostheses are being developed to help amputees handle several different activities: standing, level walking, stepping up and down, walking up and down a ramp, etc. For each walking mode, a different control policy is required to control the prosthesis. User intent recognition system plays an important role to infer the user's activity mode while transitioning from one walking mode to another one, and then to activate the appropriate controller. Pattern recognition techniques are used to address such problems.

In this research, mechanical sensor signals are experimentally collected from an able-bodied subject, and comprise the training inputs to the UIR system. Signals are processed and filtered to eliminate noise and to handle missing data points. Signals reflecting the state of the prosthesis, user-prosthesis interactions, and prosthesis-environment interactions are used for user intent recognition. Hip and ankle angles, ground reaction force (GRF) along three axes, and hip moment are chosen as relevant input signals that reflect various gait modes. Principal component analysis is used to convert data to a lower dimension by eliminating the least relevant features. We propose the use of correlation analysis to remove highly correlated observations from the training set.

The main component of the UIR system is its classifier. We use K-nearest neighbor (KNN) as a classification method for this purpose. KNN is modified and optimized with an evolutionary algorithm for enhanced performance. We also modify KNN so that the contribution of each neighbor is weighted on the basis of its distance to the test point, and on the basis of the history of previously classified test points. This modification leads to better performance than standard KNN. Optimization techniques can be used to tune the KNN parameters and obtain a classification system with the highest possible accuracy. We choose biogeography-based optimization (BBO) as the evolutionary optimization algorithm for this purpose. The optimization problem is to minimize the classification error. The UIR system can then be used to identify unknown walking activities. The architecture of the UIR system is illustrated in Fig. 1. We use MATLAB to implement user intent recognition. BBO is a stochastic algorithm, so it requires several runs to optimize the parameters. We use parallel computing to reduce the optimization time from 7.8 days to about 20 h [11]. To test the proposed method, multiple sets of experimental data are collected for various gait modes: standing (ST), slow walking (SW), normal walking (NW), and fast walking (FW). Figure 2 illustrates the experimental setup for able-bodied subjects. Future work will extend the proposed approach to amputee gait data. Figure 3 shows an example of test data for a walking trial lasting approximately 18 s, which includes different walking modes.

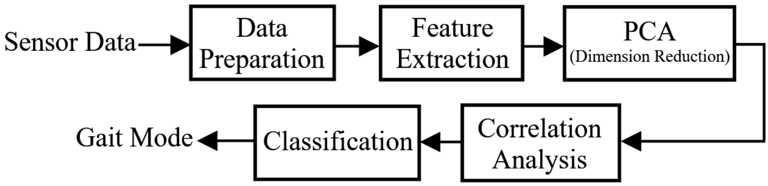


Fig. 1. Architecture of user intent recognition system: an evolutionary algorithm (not shown) is used to optimize the system components

Fig. 2. Experimental setup: data collection for user intent recognition for able-bodied subjects

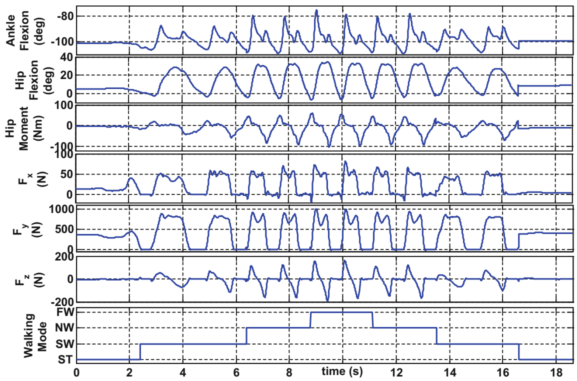


Fig. 3. Sample test data showing four different gait modes and transitions: ST (standing), SW (slow walk), NW (normal walk), and FW (fast walk)

Table 1 shows the performance of different versions of KNN. The first row of Table 1 shows simple KNN, which uses $K = 7$ nearest neighbors and results in 12.9% test error. Test error reduces to 11.5% if we use weighted KNN with $K = 7$ nearest neighbors. Test error is 8.06% when weighted KNN is used in addition to previously classified gait modes to inform the current classification mode. The fourth row of Table 1 shows that the optimized weighted KNN with information from previously classified modes provides the minimum classification error. Figure 4 shows the performance of the classifier using both simple KNN and optimized KNN. Classification error for optimized KNN is 3.59% compared to 12.9% with standard KNN.

In conclusion, KNN was modified to enhance the performance of a user intent recognition system. An evolutionary algorithm was applied to optimize the classifier parameters. Experimental data was used for training and testing the system. It is shown that the optimized system can classify four different walking modes with an accuracy of 96%. The code used to generate these results is available at http://embeddedlab.csuohio.edu/prosthetics/research/user-intent-recognition.html. Further details about this research can be found in [11].

Table 1. Performance of KNN for user intent recognition with different classifier parameters

Method	Train error	Test error
Simple KNN ($K = 7$)	7.41%	12.9%
Weighted KNN ($K = 7$)	3.81%	11.5%
Weighted KNN and Recent Modes ($K = 7$)	3.44%	8.06%
Optimized KNN ($K = 12$)	3.22%	3.59%

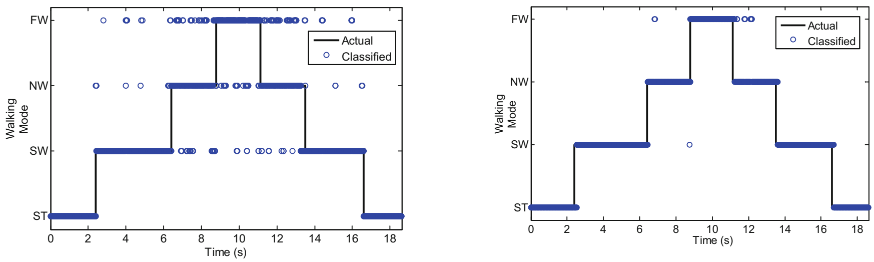


Fig. 4. User intent classifier results for optimized KNN is 3.59% error (right), which improved from 12.9% with standard KNN (left)

Stable Robust Adaptive Impedance Control of a Prosthetic Leg. We propose a nonlinear robust model reference adaptive impedance controller for a prosthesis test robot. We use an adaptive control term to compensate for the uncertain parameters of the system, and a robust control term to keep the error trajectories in a boundary layer so the system exhibits robustness to variations of ground reaction force. The algorithm not only compromises between control chattering and tracking, but also limits tracking-error-based (TEB) parameter adaptation to prevent unfavorable drift. The acceleration-free regressor form of the system obviates the need to measure joint accelerations, which would otherwise introduce noise in the system. We use particle swarm optimization (PSO) to optimize the parameters of the controller and the adaptation law. The PSO cost function is comprised of torque optimality and tracking performance.

The prosthesis is an active transfemoral (above-knee) prosthesis. The complete system model has a prismatic-revolute-revolute (PRR) joint structure. Human hip and thigh motion are emulated by a prosthesis test robot. The vertical degree of freedom represents vertical hip motion, the first rotational axis represents angular thigh motion, and the second rotational axis represents prosthetic angular knee motion [1, 2]. The three degree-of-freedom model can be written as follows:

$$M\ddot{q} + C\dot{q} + g + R = u - T_e, \tag{1}$$

where $q^T = [\, q_1 \quad q_2 \quad q_3 \,]$ is the vector of generalized joint displacements (q_1 is the vertical displacement, q_2 is the thigh angle, and q_3 is the knee angle); u is the control signal that comprises the active control force at the hip and the active control torques at the thigh and knee; and T_e is the effect of the GRF on the three joints. The contribution of this research is a nonlinear robust adaptive impedance controller using a boundary layer and a sliding surface to track reference inputs in the presence of parameter uncertainties. We desire the closed-loop system to provide near-normal gait for amputees. Therefore, we define a target impedance model with characteristics that are similar to those of able-bodied walking:

$$M_r(\ddot{q}_r - \ddot{q}_d) + B_r(\dot{q}_r - \dot{q}_d) + K_r(q_r - q_d) = -T_e \tag{2}$$

where q_r and q_d are the trajectory of the reference model and the desired trajectory respectively. Since the parameters of the system are unknown, we use the control law

$$u = \widehat{T}_e - K_d \,\mathrm{sat}(\widehat{s/\mathrm{diag}}(\varphi)) + \widehat{M}\dot{v} + \widehat{C}v + \widehat{g} + \widehat{R} \tag{3}$$

where the diagonal elements of φ are the widths of the saturation function; $s = \dot{e} + \lambda e$ and $v = \dot{q}_r - \lambda e$ are the error and signal vectors respectively; $e = q - q_r$ denotes tracking error, $\lambda = \mathrm{diag}(\lambda_1, \lambda_2, \ldots, \lambda_n)$, where $\lambda_i > 0$; $K_d = \mathrm{diag}(K_{d1}, K_{d2}, \ldots, K_{dn})$, where $K_{di} > 0$; n is the number of rigid links; and $\widehat{M}$, $\widehat{C}$, $\widehat{g}$, $\widehat{R}$, and $\widehat{T}_e$ are estimates of M, C, g, R, and T_e respectively. The control law [36] of Eq. (3) comprises two different parts. The first part, $\widehat{T}_e - K_d\mathrm{sat}(s/\mathrm{diag}(\varphi))$, satisfies the reaching condition ($\mathrm{sgn}(s)\dot{s} \leq -\gamma$, $\gamma = [\, \gamma_1 \quad \gamma_2 \quad \ldots \quad \gamma_n \,]^T$ and $\gamma_i > 0$) and handles the variations of the external inputs T_e. The second part, $\widehat{M}\dot{v} + \widehat{C}v + \widehat{g} + \widehat{R}$, is an adaptive term that handles the uncertain parameters, which are estimated via the following adaptation mechanism:

$$\dot{\hat{p}} = -\mu^{-1} Y^T(q, \dot{q}, v, \dot{v}) s_\Delta, \tag{4}$$

where $Y(q, \dot{q}, v, \dot{v})$ is an acceleration-free regressor for the left side of Eq. (1); s_Δ is the boundary layer trajectory; and μ is an $r \times r$ design matrix with positive diagonal elements. To trade off control chattering and tracking accuracy, and to create an adaptation dead zone to prevent unfavorable parameter drift, we define a trajectory s_Δ as follows [1, 2, 39]:

$$s_\Delta = \begin{cases} 0, & |s| \leq \mathrm{diag}(\varphi) \\ s - \varphi\,\mathrm{sat}(s/\mathrm{diag}(\varphi)), & |s| > \mathrm{diag}(\varphi) \end{cases} \tag{5}$$

where s_Δ is an n-element vector; the region $|s| \leq \mathrm{diag}(\varphi)$ is the boundary layer and the inequality is interpreted element-wise; and the diagonal elements of φ are the boundary layer thicknesses and the widths of the saturation function so that $\varphi = \mathrm{diag}(\varphi_1, \varphi_2, \ldots, \varphi_n)$ and $\varphi_i > 0$.

To perform a stability analysis of the controller, the following positive-definite Lyapunov function is considered:

$$V(s_\Delta, \tilde{p}) = \frac{1}{2}\left(s_\Delta^T M s_\Delta\right) + \frac{1}{2}\left(\tilde{p}^T \mu \tilde{p}\right). \tag{6}$$

Let us assume that $\left|\widehat{T}_{e_i} - T_{e_i}\right| \leq F_i \leq F_m$, $\gamma_m = \max(\gamma_i)$, and a is a positive scalar. Given the Lyapunov function of Eq. (6), the control law of Eq. (3), and the TEB adaptation mechanism of Eq. (4) in conjunction with the boundary layer trajectory of Eq. (5), if $K_{di} \geq -a\dot{q}_{max}\varphi_i + F_m + \gamma_m$, then $\dot{V}(s_\Delta, \tilde{p}) \to 0$ as $t \to \infty$, which means that $s_\Delta \to 0$ and the controller guarantees the convergence of the error trajectories to the boundary layer after the adaptation period.

We use PSO to tune the controller and estimator parameters. PSO decreases the cost function (a blend of tracking and control costs) by 8%. We suppose the system parameters can vary by ±30% from their nominal values. Figure 5 compares the states of the closed-loop system with the desired trajectories when the system parameters vary. The MATLAB code used to generate these results is available at http://embeddedlab.csuohio.edu/prosthetics/research/robust-adaptive.html [2].

Hybrid Function Approximation-Based Impedance Control for Prosthetic Legs. In our previous research [7] we developed a process to combine the different control schemes of a prosthesis test robot and a prosthetic leg to yield a stable system. We assumed that the prosthesis test robot was controlled with Slotine and Li's regressor-based controller while the prosthesis was controlled with a regressor-free controller. We addressed this problem by defining a framework within which two controllers could be systematically combined by maintaining their indirect dependence on each other, and we developed a theorem that proved that the combined robotic system was stable, and we showed the efficacy of the system using simulation results. However, the goal of the controllers in [7] was pure motion tracking in the presence of external disturbances. As a result, we obtained good reference trajectory tracking but relatively high control signal magnitudes.

In an effort to reduce the effects of external disturbances, or ground reaction forces (GRFs), we augment impedance control, which is a form of environmental interaction

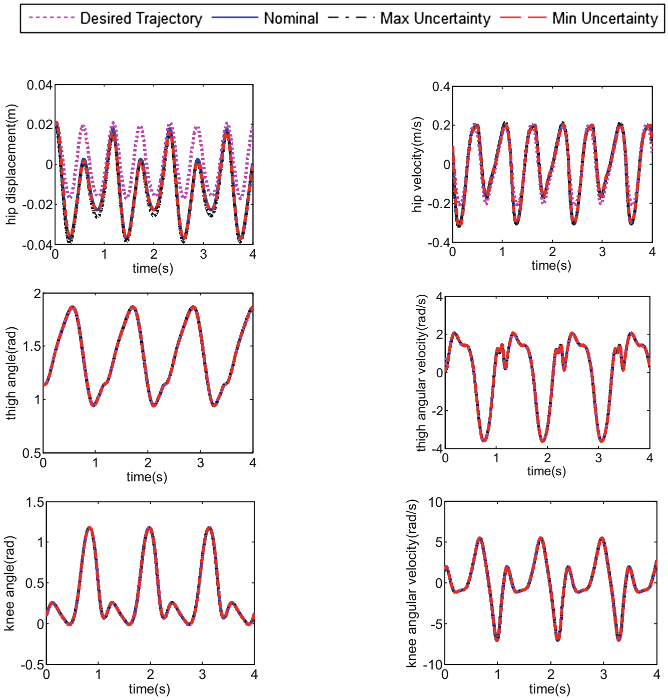


Fig. 5. Joint displacements and velocities with stable robust adaptive impedance control

control, to our previously developed hybrid control scheme. Impedance control gives the modified control scheme the ability to trade off trajectory tracking with control signal magnitude, depending on the nature of the GRFs.

The combination of the prosthesis test robot and the prosthetic leg can be described by the dynamic equations of a rigid robot under the influence of external forces [29, 39]. We use pure motion tracking as the goal of the prosthesis test robot and impedance control as the goal of the prosthetic leg. For impedance control we design a controller such that the closed-loop system behaves like the target impedance

$$M_i(\ddot{q}_r - \ddot{q}_d) + B_i(\dot{q}_r - \dot{q}_d) + I_i(q_r - q_d) = -T_e \tag{7}$$

where $q_r \in \mathbb{R}^n$ and $q_d \in \mathbb{R}^n$ are the reference and desired trajectory respectively, $M_i \in \mathbb{R}^{n \times n}$, $B_i \in \mathbb{R}^{n \times n}$, and $I_i \in \mathbb{R}^{n \times n}$ are the apparent inertia, damping, and stiffness respectively, and $T_e \in \mathbb{R}^n$ captures the external torques and forces applied to the coupled robotic system.

We use MATLAB/Simulink to simulate the system's behavior with the proposed controller, which is a combination of regressor-free environmental interaction control and regressor-based pure motion tracking control; see Figs. 6 and 7. Figure 6 shows good tracking of the reference trajectories for hip displacement, hip angle, and knee angle. The controller for the knee angle gives reasonable trade-offs in tracking and control signal magnitude when under the influence of GRFs, and then resumes tight reference trajectory tracking when there is no GRF.

In Fig. 7 we see that the control signal magnitudes for the hip displacement, hip angle, and knee angle are relatively low, and the vertical GRF is comparable to that experienced during able-bodied walking.

In conclusion, the simulation results show the combination of two different robotic systems with different control schemes. The simulation results show that impedance control is valuable in reducing control signal magnitudes, and hence preventing damage to equipment and reducing strain on amputees.

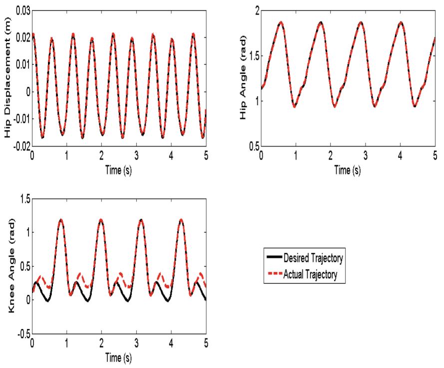


Fig. 6. Joint angle trajectories with hybrid function approximation-based impedance control

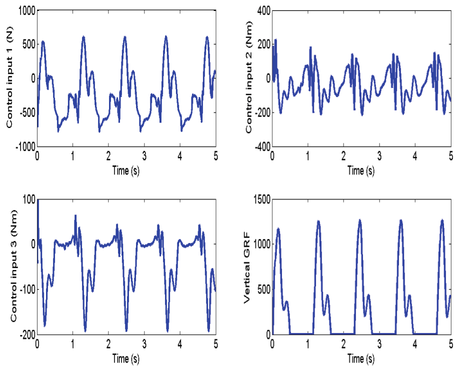


Fig. 7. Control signals and vertical ground reaction force with hybrid function approximation-based impedance control

System Identification and Control Optimization of a Prosthetic Knee. In this research, an EMG-30 geared DC motor is installed in a Mauch SNS knee to create an active prosthesis. The Mauch SNS knee is a widely used passive prosthesis; we adapted it here by detaching the damper connection and driving it with a DC motor.

Our work provides a basic framework for system identification, control optimization, and implementation of an active prosthetic knee during swing phase. To apply velocity control to the system, proportional-integral-derivative control (PID) is utilized due its applicability to an extensive variety of systems, its simplicity, and its ease of use with embedded systems technology. The objective of this research is parameter investigation for PID with respect to prosthetic leg shank length. To accomplish this objective, we first need to develop a prosthetic leg model. We use heuristic algorithms and gradient descent algorithms to identify model parameters and tune the PID controller.

Particle swarm optimization, biogeography-based optimization (BBO) and sequential quadratic optimization (SQP) [18, 20, 32, 37] are selected for identification and tuning. The reason for using more than one optimization algorithm is to avoid local minimum solutions, to discover which algorithm is superior for this task, and to discover how sensitive each heuristic algorithm is to its own parameters.

Hardware setup includes a servo system composed of a desktop PC connected to a Quanser© DAQ card, Matlab with Quanser Quarc software for real-time connectivity, and DAQ hardware; see Fig. 8. The DAQ system delivers an analog control signal to a servo amplifier to drive the EMG30 DC motor. An axial quadrature encoder sends signals through two digital channels. A Mauch SNS knee is attached to an EMG-30 geared DC motor to comprise our active leg prosthesis.

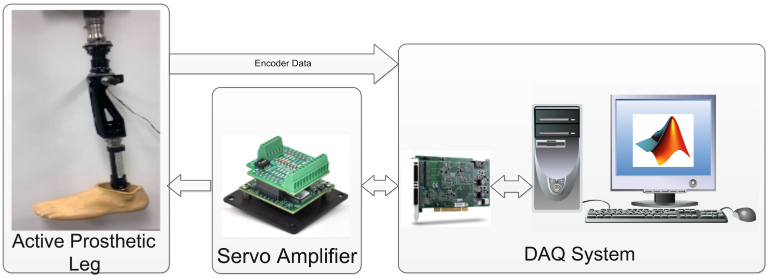


Fig. 8. Hardware setup for system identification and control optimization

Numerical differentiation is usually used to obtain angular velocity by differentiating the encoder signal [42]. This technique often leads to a highly distorted signal due to encoder resolution. Therefore, a Kalman filter is designed to estimate the angular velocity. The DC geared motor and the Mauch SNS are described mathematically in [10]. Matlab Simulink is used to build simulation models. In order to identify model parameters and obtain average performance metrics, optimization algorithms execute 20 times each. The DC motor model and Mauch knee joint model are combined to form the active prosthetic leg model.

In order to see how sensitive BBO and PSO performances are, a sensitivity analysis test is carried out for each algorithm. We say that an algorithm's sensitivity to one of its parameters is "High," "Medium," or "Low," if a given percentage parameter variation leads to a deviation from the best solution by less than 10%, 10–25%, or more than 25%, respectively. Tables 2 and 3 show the algorithm parameter values and their sensitivities.

Table 2. BBO algorithm parameter sensitivity

	Lowest value	Highest value	Test increment	Best value	Sensitivity
Number of generations	50	125	25	**100**	Medium
Population size	50	100	10	**60**	Medium
Mutation probability	5%	20%	5%	**10%**	High
Number of elites	1	5	1	**2**	High

Table 3. PSO algorithm parameter sensitivity

	Lowest value	Highest value	Test increment	Best value	Sensitivity
Number of generations	50	250	50	**100**	Medium
Population size	50	100	10	**60**	Low
Correction factor	0.5	3	0.5	**2**	Medium
Acceleration constant	1	5	1	**0.5**	High
Cognitive parameter	0.05	1	0.05	**0.1**	High
Social parameter	0.1	0.5	0.1	**0.3**	High

The active prosthetic knee model and PID are used to build a closed-loop feedback system. To investigate PID controller parameter behavior with respect to shank length, we use the optimization algorithms to tune the controller parameters (K_p, K_i and K_d). Results show that for model parameter identification, particle swarm optimization gives the best optimization results, and BBO gives better average overall performance than SQP. For PID tuning, BBO achieves the best average overall performance, but PSO shows the fastest average convergence. Finally, we see that increasing shank length results in an increase in the optimal proportional gain, and a decrease in the optimal differential and integral gains; see Fig. 9.

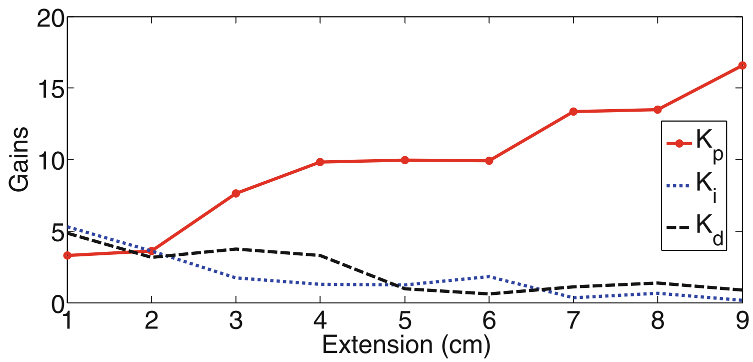


Fig. 9. PID parameter values with respect to shank length

Ground Reaction Force Estimation with an Extended Kalman Filter. A method to estimate GRF in a robot/prosthesis system is presented. The system includes a robot that emulates human hip and thigh motion, and a powered prosthesis for transfemoral amputees, and includes four degrees of freedom: vertical hip displacement, thigh angle, knee angle, and ankle angle. A continuous-time extended Kalman filter (EKF) [38] estimates the states of the system and the GRFs that act on the prosthetic foot.

The system includes eight states: q_1 is vertical hip displacement, q_2 is thigh angle, q_3 is knee angle, q_4 is ankle angle, and their derivatives. Horizontal and vertical GRF is applied to the toe and heel of a triangular foot. The ground stiffness is modeled to simulate GRF. The initial state $x(0)$ is obtained from reference data, and we randomly initialize the estimated state $\hat{x}(0)$ to include estimation error. The diagonal covariance matrices of the continuous-time process noise and measurement noise are tuned to obtain good performance. Results are shown in Fig. 10. Even with significant initial estimation errors, the EKF converges to the true states quickly.

The performance of the EKF may deteriorate significantly with modeling uncertainties. The H_∞ filter [38] was designed to improve the robustness of state estimation in the presence of modeling errors. Here we assume that the robot/prosthesis system parameters vary by $\pm 10\%$ from their nominal values. In this test the initial value of the state vector $x(0)$ and the measurement and process noise covariances R and Q are identical to those used in the EKF. We also set the initial value of the estimated state vector $\hat{x}(0)$ to provide an arbitrary but nonzero initial estimation error. The tuning parameters in the H_∞ filter are chosen by the trial and error to obtain good performance. The RMS estimation errors of the two filters are compared in Tables 4 and 5 when $\pm 10\%$ uncertainty on the system parameters is imposed. We see that the H_∞ filter generally performs better than the EKF. However, the EKF still works well.

Table 4. Comparison between EKF and H_∞ filters in terms of RMSE when the system parameters (SPs) deviate from their nominal values by +10%

SPs	$x_1, (m)$	$x_2, (rad)$	$x_3, (rad)$	$x_4, (rad)$	$x_5, (m/s)$	$x_6, (rad/s)$
EKF	0.005	0.007	0.03	0.02	0.06	0.12
H_∞	0.001	0.005	0.01	0.01	0.03	0.12
SPs	$x_7, (rad/s)$	$x_8, (rad/s)$	$x_9, (N)$	$x_{10}, (N)$	$x_{11}, (N)$	$x_{12}, (N)$
EKF	0.47	1.09	4.1	19	7.8	33
H_∞	0.44	0.36	1.5	7.5	5.7	25

Table 5. Comparison between EKF and H_∞ filters in terms of RMSE when the system parameters (SPs) deviate from their nominal values by −10%

SPs	$x_1, (m)$	$x_2, (rad)$	$x_3, (rad)$	$x_4, (rad)$	$x_5, (m/s)$	$x_6, (rad/s)$
EKF	0.007	0.005	0.03	0.02	0.07	0.14
H_∞	0.002	0.005	0.01	0.03	0.03	0.11
SPs	$x_7, (rad/s)$	$x_8, (rad/s)$	$x_9, (N)$	$x_{10}, (N)$	$x_{11}, (N)$	$x_{12}, (N)$
EKF	0.45	1.10	5.5	19	6.2	31
H_∞	0.44	0.44	2.8	9.3	4.5	22

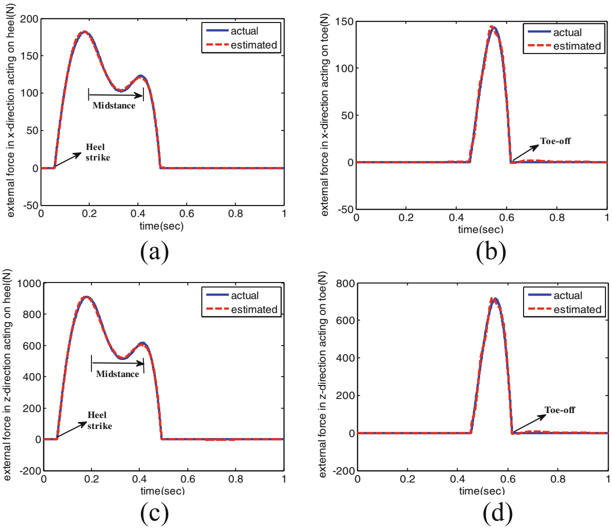


Fig. 10. Horizontal and vertical ground force (GRF) estimation

Electronic Energy Converter Design for Regenerative Prosthetics. Prosthetic models use ideal electromechanical actuators for knee joints, which do not include energy regeneration. In order to focus on energy regeneration, a voltage source converter is designed in this research to interface an electric motor to a supercapacitor.

The converter is designed to resemble a typical H-bridge motor driver. The voltage converter control system allows power to flow from the motor to the capacitor (motor mode) and from the capacitor to the motor (generator mode). During motor mode, the voltage converter's control system modulates the voltage applied to the motor using two circuits; one with the capacitor connected (powering the motor from the capacitor) and one with the capacitor disconnected (shorting the motor connection through the H-bridge). During generator mode, the voltage converter control system changes the impedance connected to the motor using two circuits; one with the capacitor connected (charging the capacitor) and one with the capacitor disconnected (allowing the motor to move with less resistance from the electronics). The circuit and motor are modeled with state space equations using MATLAB and Simulink software.

The converter is augmented to a previously developed mechanical prosthesis model [21]. The model includes the mechanical dynamics of the prosthesis, a ground contact model, and a robust tracking/impedance controller. The controller calculates desired joint torques to achieve trajectory tracking of abled-bodied reference data. The converter replaces the ideal knee motor actuator in this prosthesis model. Since torque and current are proportionally related through the motor dynamics, the tracking/impedance controller is modified to command a desired current that the converter applies through the knee motor to create the desired torque at the knee joint.

A neural network creates an inner control loop for the converter to generate the commanded motor current while the tracking/impedance controller determines torques to meet the tracking and impedance goals for the prosthesis. The neural network includes an input node which compares the motor current generated by the converter to the desired motor current commanded by the tracking/impedance controller. In addition to the error signal of the motor current, a measured ground reaction force input node is used to determine if the prosthesis is in a stance phase or swing phase, a measured velocity input node is used to determine the direction of motor rotation, and a measured torque input node is used to indicate whether the prosthesis is operating in the motoring or generating mode. The neural network contains a single output node which commands a change in duty cycle for the converter to modulate the power flow between the capacitor and the knee motor to achieve the motor torque commanded by the tracking/impedance controller.

The controller gains for the tracking/impedance controller and neural network controller, as well as the physical parameters such as the capacitance of the capacitor and the length of the prosthesis transmission links, are optimized with BBO. The system is optimized using a single set of desired trajectories (hip displacement, hip rotation, knee rotation, and ankle rotation). The control gains and physical parameters selected by BBO achieve the optimization objective of knee angle tracking with a root mean square (RMS) error of 0.13° during five seconds of simulated walking. The selected control gains and physical parameters are then used with test sets of walking data to ensure that the system can maintain tracking with different trajectories. The prosthesis maintains knee angle tracking with an RMS error of 1° with seven different sets of data during five seconds of walking. One representative set of data is shown in Fig. 11. Some data sets show a loss of energy in the capacitor, but the best case results in an increase of 67 Joules of energy during five seconds of walking. The transfer of energy between the knee and capacitor is shown in Fig. 12. It is observed that the capacitor charges as the knee motor produces excess energy and the capacitor discharges as the knee motor consumes energy.

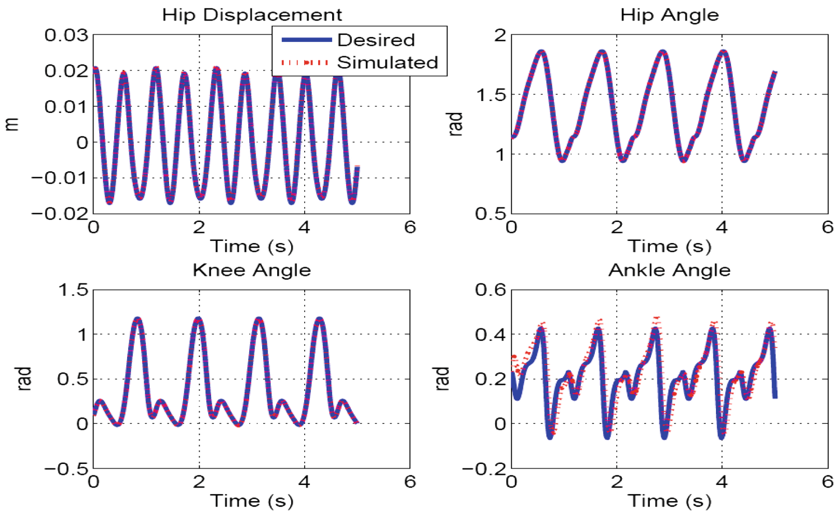


Fig. 11. Reference and simulated trajectories of hip displacement, hip rotation, knee rotation, and ankle rotation during five seconds of walking

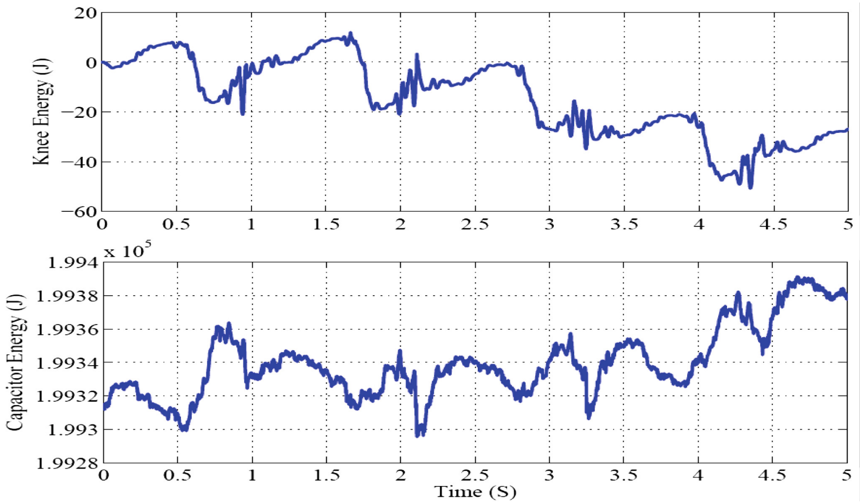


Fig. 12. Comparison between energy produced at the knee and energy stored in the capacitor

Fuzzy Logic for Robot Navigation. This research uses fuzzy logic to find a path for a mobile robot to navigate in an environment with both static and dynamic obstacles when the robot does not have any prior information about the obstacle locations. The robot stores the coordinates of previously visited locations in memory to avoid getting stuck in dead ends.

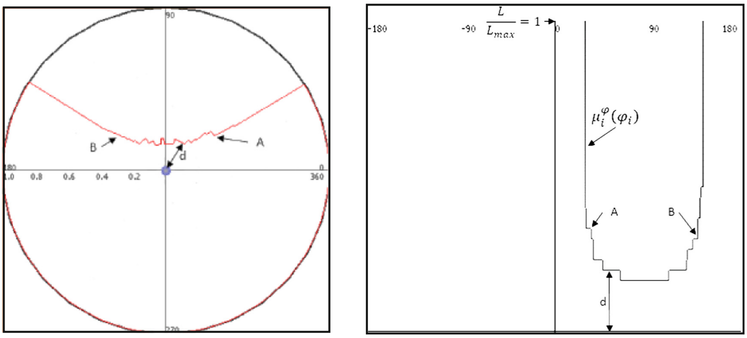
The robot radar returns a fuzzy set based on the distance L_i from obstacle i (see Fig. 13): $\mu_i^{\varphi}(\varphi_i) = \frac{L_i}{L_{max}}$. The robot finds the angle between its position and the target position, which we call α. If the robot moved in the α direction in an obstacle-free environment it would follow a direct line to the target. However, there are obstacles in the path. To find a safe path around the obstacles, we introduce a Gaussian fuzzy set [13, 14, 28, 43] which has a maximum value at α:

$$\mu_i^{\alpha}(\varphi_i) = e^{-\left(\frac{(\varphi_i-\alpha)^2}{2\sigma^2}\right)}.$$

We combine $\mu_i^{\varphi}(\varphi_i)$ and $\mu_i^{\alpha}(\varphi_i)$ to obtain a new fuzzy set, $\mu_i^{\psi}(\psi_i)$, shown in Fig. 13.

$$\mu_i^{\psi}(\varphi_i) = \min(\mu_i^{\alpha}(\varphi_i), \mu_i^{\varphi}(\varphi_i))$$

The movement direction is the maximum point in $\mu_i^{\psi}(\psi_i)$, which we call φ_A. If the robot moves with angle of φ_A, it will touch the obstacles. We therefore introduce a new fuzzy set that has the value 1 in a range of 120° around φ_A:



(a) (b)

Fig. 13. (a) A polar radar map in the presence of an obstacle, and (b) its transformation to Cartesian coordinates

$$\mu_1^{\theta}(\varphi_i) = \begin{cases} 1 & |\varphi_i - \varphi_A| < 60 \\ 0 & \text{otherwise} \end{cases}$$

In the next step we defuzzify $\mu^{\psi}(\varphi_i) * \mu_1^{\theta}(\varphi_i)$ using center of mass defuzzification [31], which is shown in Fig. 14.

Simulations confirm that the proposed approach provides reliable navigation. However, the robot is only able to get to the target point if it does not enter a dead end zone. Examples of dead end zones include rooms, single-entry areas, and other situations where the robot needs to move backward to find the path to the target. In practical applications, we cannot guarantee that a map won't have dead end zones.

The robot therefore saves visited paths in memory. The data in the robot's memory is a list of coordinates which we call Memory Points (MPs). The robot should avoid visiting the same place multiple times and it should be able distinguish between locations that were visited in the recent and in the distant past. To achieve this goal, we assign weights to each coordinate in memory (w). Weights change based on the distance to the robot. Their values are calculated with a derivative of a Gaussian distribution as shown in Fig. 15 and as described by the following:

$$w_i(MP_i) = \left| \frac{-de^{-\left(\frac{d^2}{2\sigma^2}\right)}}{\sigma} \right|, \quad \text{where} \begin{cases} d = \sqrt{(x_{MP_i} - x_{RP_i})^2 + (y_{MP_i} - y_{RP_i})^2}, \\ \qquad i = 1, 2, \ldots, N \end{cases}$$

N is the number of MPs in memory and RP is the current position of the robot. With this weighting function, the robot is more likely to visit very recent and very old locations and tends to avoid coordinates that are in between.

In different layouts and different robot and target positions, the robot can find a path to the target point successfully; see Fig. 16.

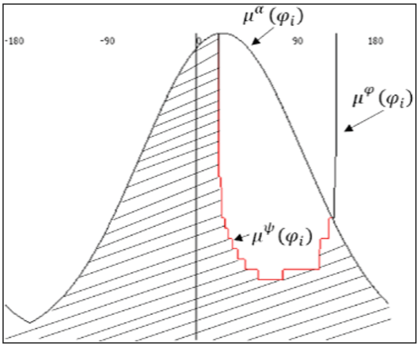


Fig. 14. Shaded area is $\mu_i^{\psi}(\psi_i)$

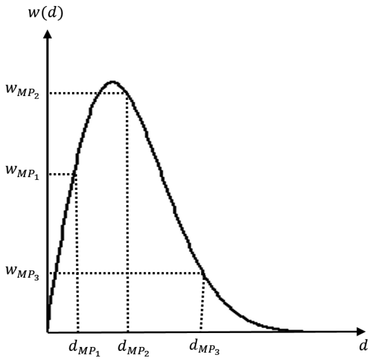


Fig. 15. Weight distribution of Memory Points for robot path planning

5 Education and Research Integration

The seven research projects described in the preceding section have a common educational core which enables their success. This section reviews those common elements.

First, most of the students involved in research come to CSU with the promise of multi-year research funding. Most funding comes from external agencies, such as the US government or industry. Some funding comes from the limited resources within CSU. In order to be productive researchers, students need to be devoted full-time to their studies and research, and they need to be worry-free with regards to finances. Successful research depends on funding, and funding depends on faculty.

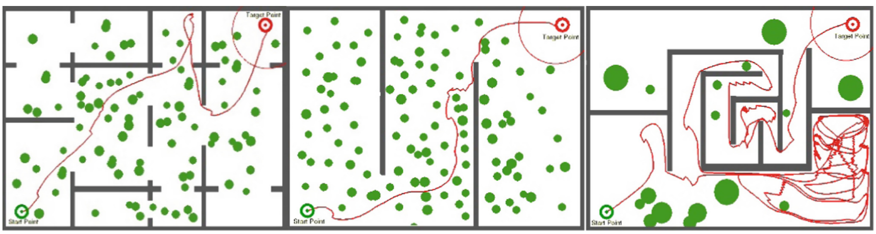


Fig. 16. Fuzzy robot path planning results: the red line is the robot path from start to target, and the green circles are dynamic obstacles. (Color figure online)

Second, research students are involved not only in coursework and research, but also in teaching-assistant duties. Some students assist with labs, tutoring, and grading, while other students are given sole responsibility for an entire undergraduate course, depending on their experience level. Superficially, this detracts from their research. However, in the long run, it enhances their research by providing them with training in the area of communication skills, problem solving, and networking.

Third, most research students are recruited as doctoral students, who are more serious about research than master's students. Some students enter CSU as master's students, but always with the intent of ultimately progressing to doctoral studies.

Fourth, research students are required to attend and present at weekly research seminars at CSU. These seminars provide the students with opportunities to learn from each other and from faculty, to network with each other, and to practice their communication skills. This indicates the need for a critical mass of research students in order to ensure a successful research enterprise.

Fifth, research students are required to publish and present their research at one or more international conferences each year. This provides them with similar benefits as the weekly seminars discussed above, but at a larger scale.

Sixth, research students with varying levels of experience and disciplinary focus all work together. Research participants include faculty, post-doctoral scholars, visiting scholars, doctoral students, master's students, and undergraduate students. Diversity also intentionally includes gender, ethnicity, and nationality. This diversity allows research students to be involved in both receiving and providing mentoring, and in learning to work across comfortable boundaries.

Seventh, research students are given as much responsibility as possible in the conduct of their research, and this responsibility gradually increases as the students gain experience. Faculty advisors fill the role of advising, but generally try to keep a hands-off approach in the daily conduct of student research. This approach teaches students to be proactive in solving problems, to take the initiative in seeking advice, and to take responsibility for their research. Faculty advisors are responsible to help students find the right balance so that the students don't go down the wrong research path or stall in their research efforts.

Many educational factors are involved in successful research. The above factors are just a few. Many more could be incorporated at CSU and other universities. But the most important consideration here is that in order to be successful, faculty must take an intentional approach to integrating education and research, and to graduating research students who are prepared to take the lead in the next generation.

6 Conclusions

The authors have described university student training. The description has focused on student participation in the US NSF project "Optimal prosthesis design with energy regeneration" and the application of ICT and modelling technologies.

Several factors play an important role in the results of this chapter. Student research requires skill in programming and software, and a broad theoretical knowledge in computer science, and mechanical, electrical, and control engineering. Students used MATLAB, Simulink, and toolboxes (Optimization, Fuzzy Logic, etc.), and programming in C and C++. The software used for robot trajectory planning research was designed and written by students in C++, and the GUI was designed using Qt and OpenGL. Standard libraries were used to make the software cross-platform.

The most important foundation for student research is theoretical knowledge in fundamental and elective disciplines such as Circuits, Linear Systems, Control

Systems, Nonlinear Control, Machine Learning, Artificial Intelligence, Intelligent Controls, Optimal State Estimation, Optimal Control, Embedded Systems, Robot Modeling and Control, Probability and Stochastic Processes, Population-Based Optimization, and Prosthesis Design and Control, which provides a basic understanding of human biomechanics and lower-limb prosthesis design and control. These courses played a vital role in the proper grounding of basic and advanced ICT and control theory for robotic and prosthetic leg research. The facilities at CSU and funding from the NSF significantly helped in furthering student research-based education.

Finally, student participation in government-sponsored research, student exchanges of research experiences with each other, and publication of research results in high-caliber journals and conferences [1, 2, 7, 11, 18, 29], provide students with effective training and self-confidence in their higher education. Research-based education also allows students to obtain practical experience as research assistants, with corresponding responsibilities in the development and implementation of research projects.

Student participation in real-world research significantly influences their engineering and research qualifications by: (a) giving them a strong understanding of ICT and engineering concepts that are covered in corresponding courses; (b) giving them practical experience and the ability to apply theoretical knowledge; (c) giving them the opportunity to learn technical material independently; (d) helping them improve fundamental skills to apply in other research in their future; (e) providing them with a rich interdisciplinary research environment; and (f) providing them with an understanding of concepts both familiar and unfamiliar. Through extensive literature review and actively seeking ways to solve research problems, students are prepared to make meaningful future contributions to the field of ICT and control engineering.

Acknowledgements. The authors thank the Fulbright Program (USA) for supporting Prof. Y.P. Kondratenko with a Fulbright 2015-2016 scholarship and for making it possible for this team to conduct research in together in the USA. This research was partially supported by US NSF Grant 1344954.

References

1. Azimi, V., Simon, D., Richter, H., Fakoorian, S.A.: Robust composite adaptive transfemoral prosthesis control with non-scalar boundary layer trajectories. In: Proceedings of the American Control Conference (ACC), Boston, MA, USA (2016)
2. Azimi, V., Simon, D., Richter, H.: Stable robust adaptive impedance control of a prosthetic leg. In: Dynamic Systems and Control Conference, Columbus, Ohio, USA, October 2015
3. Bredeweg, B., Forbus, K.D.: Qualitative modeling in education. AI Mag. **24**(4), 35–46 (2003). American Association for Artificial Intelligence
4. Chou, C., Tsai, C.-C.: Developing web-based curricula: issues and challenges. J. Curriculum Stud. **34**(6), 623–636 (2002)
5. Clements, D.H.: Curriculum research: toward a framework for "Research-Based Curricula". J. Res. Math. Educ. **38**(1), 35–70 (2007)
6. Conditt, M.A., Noble, P.C., Thompson, M.T., Ismaily, S.K., Moy, G.J., Mathis, K.B.: A computerized bioskills system for surgical skills training in total knee replacement. Proc. Inst. Mech. Eng. Part H J. Eng. Med. **221**(1), 61–69 (2007)

7. Ebeigbe, D., Simon, D., Richter, H.: Hybrid function approximation based control with application to prosthetic legs. In: IEEE International Systems Conference, Orlando, FL, USA, April 2016
8. Gáti, J., Kártyás, G.: Computer system support for higher education programs in engineering. In: Proceedings of 4th International Conference on Emerging Trends in Engineering and Technology (ICETET), pp. 61–65 (2011)
9. Gilbert, J.K.: Models and modelling: routes to more authentic science education. Int. J. Sci. Math. Educ. **2**(2), 115–130 (2004)
10. Gonçalves, J., Lima, J., Costa, P., Moreira, A.P.: Modeling and simulation of the EMG30 geared motor with encoder resorting to SimTwo: the official Robot@Factory simulator. In: Azevedo, A. (ed.) Advances in Sustainable and Competitive Manufacturing Systems, pp. 307–314. Springer, Heidelberg (2013)
11. Khademi, G., Mohammadi, H., Simon, D., Hardin, E.C.: Evolutionary optimization of user intent recognition for transfemoral amputees. In: IEEE Biomedical Circuits and Systems Conference (BioCAS), Atlanta, Georgia, USA, pp. 1–4 (2015)
12. Kondratenko, Y.P., Kondratenko, G.V.: Robotic system with myoelectric adapting for rehabilitation tasks. ACTA Bioeng. Biomech. **3**, 1–6 (2001)
13. Kondratenko, Y., Kondratenko, V.: Soft computing algorithm for arithmetic multiplication of fuzzy sets based on universal analytic models. In: Ermolayev, V., Mayr, H., Nikitchenko, M., Spivakovsky, A., Zholtkevych, G. (eds.) Information and Communication Technologies in Education, Research, and Industrial Application. Communications in Computer and Information Science, vol. 469, pp. 49–77. Springer, Cham (2014)
14. Kondratenko, Y.P., Klymenko, L.P., Al Zu'bi, E.Y.M.: Structural optimization of fuzzy systems' rules base and aggregation models. Kybernetes **42**(5), 831–843 (2013)
15. Kondratenko, Y., Khademi, G., Azimi, V., Ebeigbe, D., Abdelhady, M., Fakoorian, S.A., Barto, T., Roshanineshat, A.Y., Atamanyuk, I., Simon D.: Information, communication, and modeling technologies in prosthetic leg and robotics research at Cleveland State University. In: Ermolayev, V., et al. (eds.) Proceedings of 12th International Conference on Information and Communication Technologies in Education, Research, and Industrial Application, 21–24 June 2016, Kyiv, Ukraine, ICTERI 2016, vol. 1614, pp. 168–183. CEUR-WS (2016)
16. Kondratenko, Y., Simon, D., Atamanyuk, I.: University curricula modification based on advancements in information and communication technologies. In: Ermolayev, V., et al. (eds.) Proceedings of 12th International Conference on Information and Communication Technologies in Education, Research, and Industrial Application, 21–24 June 2016, Kyiv, Ukraine, ICTERI 2016, vol. 1614, pp. 184–199. CEUR-WS (2016)
17. Louca, L.T., Zacharia, Z.C.: The use of computer-based programming environments as computer modelling tools in early science education: the cases of textual and graphical program languages. Int. J. Sci. Educ. **30**(3), 287–323 (2008)
18. Ma, H., Simon, D.: Biogeography-based optimization with blended migration for constrained optimization problems. In: Proceedings of the 12th Annual Conference on Genetic and Evolutionary Computation, New York, NY, USA, pp. 417–418 (2010)
19. McKee, N.H., Agur, A.M., Tsang, W., Singh, K.S.: Possible uses of computer modeling of the functioning human hand. Clin. Plast. Surg. **32**(4), 635–641 (2005)
20. Mo, H., Xu, Z.: Research of biogeography-based multi-objective evolutionary algorithm. In: Khosrow-Pour, M. (ed.) Interdisciplinary Advances in Information Technology Research, pp. 125–135 (2013)
21. Mohammadi, H., Richter, H.: Robust tracking/impedance control: application to prosthetics. In: American Control Conference, Chicago, Illinois, July 2015 (2015)

22. Musa, A., Al-Dmour, A., Fraij, F., Gonzalez, V., Al-Hashemi, R.: Developing a virtual laboratory for a communication and computer networking course. Int. J. Continuing Eng. Educ. Life Long Learn. **20**(3–5), 390–406 (2010)
23. Nehrir, M.H., Fatehi, F., Gerez, V.: Computer modeling for enhancing instruction of electric machinery. IEEE Trans. Educ. **38**(2), 166–170 (1995)
24. Nemanjic, B., Svetozar, N.: Computer Simulations: Technology, Industrial Applications and Effects on Learning. Nova Science Publishers Inc., New York (2012)
25. Neptune, R.R.: Computer modeling and simulation of human movement. Sci. Principles Sports Rehabil. **11**(2), 417–434 (2000)
26. Panselinas, G.E., Komis, V.: Using educational software to support collective thinking and test hypotheses in the computer science curriculum. Educ. Inform. Technol. **16**(2), 159–182 (2011)
27. Patil, L.S., Patil, K.D., Thosar, A.G.: The role of computer modeling and simulation in power electronics education. In: Proceedings of the 2nd International Conference on Emerging Trends in Engineering and Technology (ICETET), pp. 416–419 (2009)
28. Piegat, A.: Fuzzy Modeling and Control. Springer, Heidelberg (2001). doi:10.1007/978-3-7908-1824-6
29. Richter, H., Simon, D., Smith, W., Samorezov, S.: Dynamic modeling, parameter estimation and control of a leg prosthesis test robot. Appl. Math. Model. **39**, 559–573 (2015)
30. Richter, H., Simon, D.: Robust tracking control of the prosthesis test robot. J. Dyn. Syst. Measur. Control **136**(3), Paper No. DS-13–1052 (2014)
31. Runkler, T.: Selection of appropriate defuzzification methods using application specific properties. IEEE Trans. Fuzzy Syst. **5**(1), 72–79 (1997)
32. Sayed, M., Saad, M., Emara, H., El-Zahab, E.A.: A novel method for PID tuning using a modified biogeography-based optimization algorithm. In: Proceedings of the 24th Chinese Control and Decision Conference (CCDC), pp. 1642–1647 (2012)
33. Schonning, A.: Biomechanical applications of computers in engineering education. In: ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Las Vegas, Nevada, USA, pp. 389–393. American Society of Mechanical Engineers (2007)
34. Schwarz, C.V., Meyer, J., Sharma, A.: Technology, pedagogy, and epistemology: Opportunities and challenges of using computer modeling and simulation tools in elementary science methods. J. Sci. Teacher Educ. **18**(2), 243–269 (2007)
35. Shaalan, H.: Using software to enhance power engineering education in a technology program. IEEE Power Eng. Rev. **21**(6), 62–63 (2001)
36. Shih, N.-J.: RP-aided computer modeling for architectural education. Comput. Graph. **30**(1), 137–144 (2006)
37. Simon, D.: Evolutionary Optimization Algorithms: Biologically Inspired and Population-Based Approaches to Computer Intelligence. Wiley, Hoboken (2013)
38. Simon, D.: Optimal State Estimation: Kalman, H-infinity, and Nonlinear Approaches. Wiley, Hoboken (2006)
39. Slotine, J.-J.E., Coetsee, J.A.: Adaptive sliding controller synthesis for non-linear systems. Int. J. Control **43**(6), 1631–1651 (1986)
40. Teodoro, V.D., Neves, R.G.: Mathematical modelling in science and mathematics education. Comput. Phys. Commun. **182**(1), 8–10 (2011)
41. Van Amerongen, J., Breedveld, P.: Modelling of physical systems for the design and control of mechatronic systems. Ann. Rev. Control **27**(1), 87–117 (2003)
42. Yang, W.: Applied Numerical Methods Using MATLAB. Wiley-Interscience, Hoboken (2005)
43. Zadeh, L.A.: Fuzzy sets. Inf. Control **8**, 338–353 (1965)

44. Zhang, B.H., Liu, X.F., Krajcik, J.S.: Expert models and modeling processes associated with a computer-modeling tool. Sci. Educ. **90**(4), 579–604 (2006)
45. Zhang, Q.: GUI based computer modeling and design platform to promote interactive learning in fiber optic communications. In: Proceedings of the 37th Annual Frontiers in Education Conference - Global Engineering: Knowledge Without Borders, Opportunities Without Passports, FIE 2007, pp. S3H-14–S3H-19 (2007)