Robotics

Degrees Offered

- Graduate certificate in Robotics
- Master of Science in Robotics (non-thesis)
- Master of Science in Robotics (thesis)
- Doctor of Philosophy in Robotics

The Robotics program offers graduate certificate, Master of Science and Doctor of Philosophy degrees in Robotics. The graduate certificate is intended for working professionals. The non-thesis MS is designed to prepare candidates for industry careers in robotics. The thesis MS and PhD degrees are designed to prepare students for research careers.

Program Director

Andrew Petruska

Professors

Qi Han

Tyrone Vincent

Kevin Moore

Associate Professors

Kathryn Johnson

Hao Zhang

Xiaoli Zhang

Assistant Professors

Neil Dantam

Andrew Petruska

Thomas Williams

Qin Zhu

The Robotics program offers graduate certificate, Master of Science and Doctor of Philosophy degrees in Robotics. The graduate certificate is intended for working professionals. The non-thesis MS is designed to prepare candidates for industry careers in robotics. The thesis MS and PhD degrees are designed to prepare students for research careers.

Combined Program: The Robotics program also offers combined BS+MS degrees. These degrees offer an expedited graduate school application process and allow students to begin graduate coursework while still finishing their undergraduate degree requirements.

Admissions and Program Policies Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

MS and PhD

The minimum requirements for admission to the MS and PhD degrees in Robotics are:

• Applicants must have a Bachelor's degree, or equivalent, from an accredited institution with a grade-point average of 3.0 or better on a 4.0 scale prior to matriculating into the Robotics degree program.

• Students are expected to have completed the following coursework: 1) two semesters of calculus, 2) differential equations, and 3) data structures. The Robotics graduate admissions committee may require that students who do not meet this expectation demonstrate competency or take remedial coursework. Such coursework may not count toward the graduate degree. The committee will decide whether to recommend regular or provisional admission.

• Graduate Record Examination (Quantitative section) score of 151 or higher (or 650 on the old scale). Applicants who have graduated with a computer science, engineering, or math degree from Mines within the past five years are not required to submit GRE scores.

• Applicants who are not U.S. citizens or permanent residents and whose native language is not English, must prove English proficiency as part of the application process. Refer to the Graduate Admissions website for more details.

• For the PhD program, prior research experience is desired but not required.

Transfer Credit

Graduate-level courses taken at other universities for which a grade equivalent to a B or better was received will be considered for transfer credit with approval of the advisor and/or thesis committee, and home department head, as appropriate. Transfer credits must not have been used as credit toward a bachelor's degree. For the MS degree, no more than nine credits may transfer. For the PhD degree, up to 24 credits of courses may be transferred. In lieu of transfer credit for individual courses, students who enter the PhD program with a thesis-based master's degree from another institution may transfer up to 36 credits in recognition of the course work and research completed for that degree.

Advisor and Thesis Committees

Students must have an advisor from the Robotics faculty to direct and monitor their academic plan, research, and independent studies. Advisors must be full-time permanent members of the faculty. In this context, fulltime permanent members of the faculty are those that hold the rank of professor, associate professor, assistant professor, research professor, associate research professor or assistant research professor. Upon approval by the graduate dean, adjunct faculty, teaching faculty, visiting professors, emeritus professors and off-campus representatives may be designated additional co-advisors. A list of Robotics faculty by rank is available in the faculty tab of the catalog.

The department of the advisor is the student's home department.

Master of Science (thesis option) students in Robotics must have at least three members on their thesis committee. In addition to the institutional requirements, at least one committee member who is not the advisor must be Robotics faculty.

Robotics PhD thesis committees must have at least four members. In addition to the institutional requirements, at least one committee member who is not the advisor must be Robotics faculty.

Program Requirements

Graduate Certificate

The graduate certificate will require 12 credits of coursework. The table below summarizes the requirements for the graduate certificate.

Total Semester Hrs		12.0
	course list	
Robotics Core	Four courses, one from each focus area's core	12.0

MS Degrees

The MS degrees will require 30 credits, with thesis research options substituting for electives.

MS Non-Thesis (MS-NT)

Students must take 30 credits of coursework to complete the degree. The table below summarizes the requirements for the MS-NT degree.

Total Semester Hrs		30.0
Technical Electives	Four courses in any participating robotics department (CSCI, EDNS, EENG, MATH, MEGN)	12.0
Robotics Electives (Depth)	Two courses from robotics course list	6.0
Robotics Core (Breadth)	Four courses, one from each focus area's core course list	12.0

MS Thesis

Students must take 21 credits of coursework and 9 credits of MS thesis research to complete the degree. The table below summarizes the requirements for the MS Thesis degree.

At the conclusion of the MS thesis, the student must make a formal presentation and defense of their thesis research. A student must pass this defense to earn an MS degree.

Robotics Core (Breadth)	Four courses, one from each focus area's core course list	12.0
Robotics Electives (Depth)	Two courses from robotics course list	6.0
Technical Electives	One course in any participating robotics department (CSCI, EDNS, EENG, MATH, MEGN)	3.0
MEGN707	GRADUATE THESIS / DISSERTATION RESEARCH CREDIT	9.0
Total Semester Hrs		30.0

PhD Degree

The Robotics PhD requires 36 credits of coursework plus 36 research credits. The table below summarizes the coursework requirements. PhD

students must additionally complete a qualifying examination, a thesis proposal, and a thesis defense.

Total Semester Hrs		72 0
MEGN707	GRADUATE THESIS / DISSERTATION RESEARCH CREDIT	36.0
Technical Electives	Four courses in any participating robotics department (CSCI, EDNS, EENG, MATH, MEGN)	12.0
Robotics Electives (Depth)	Four Courses from robotics course list	12.0
Robotics Core (Breadth)	Four courses, one from each focus area's core course list	12.0

Robotics PhD Qualifying Examination

The Robotics PhD Qualifying Examination will test a student's ability to conduct research in their chosen area. The qualifier will have two components: a coursework component and a research component.

Coursework Qualifier: To satisfy the coursework component of the qualifier, the student must complete their four selected Robotics core courses with a minimum grade of B in each class.

Research Qualifier: The research qualifier consists of a research project. Robotics PhD students must take the qualifying examination by the end of their fourth semester (typically by the end of their second year). The examination will be evaluated by a committee consisting of at least the student's advisor, a Robotics-affiliated faculty member, and one additional faculty member.

For the qualifier, the student will conduct a literature review of 30-40 papers and perform a research project approaching the level necessary for a conference publication. The research project must be approved by the advisor and committee and will likely be some combination of the following:

- Design, analyze and/or simulate a novel robot system,
- Design and evaluate new algorithms or systems for an important research problem,
- Develop a new research software system,
- Solve a set of theoretical problems.

The deliverables will be a literature review (3-4 pages, IEEE style [4]), a research report (4-5 pages, IEEE style), and a research presentation (30 minutes to present, plus questions) delivered to the committee.

At the conclusion of the qualifier presentation, each committee member will vote their evaluation as one of "Strong Support," "Weak Support," or "Do not support." The student must receive at least two "Strong Support" votes to pass. In the case the student does not pass, the committee may decide to offer a "conditional pass" based on extra conditions, such as revisions to the report or additional experiments, the student must perform to pass the qualifier. The committee will set an explicit deadline for student to complete the extra conditions. If the student does not meet the extra conditions as determined by the committee by the deadline, the "conditional pass" becomes a "fail." If the student does not pass the qualifier on their first attempt (inclusive of a conditional pass), they may make one additional attempt to pass; the same conditional pass procedure may also be applied to the second attempt. A student who fails the qualifier on the second attempt may not continue in the program.

Robotics PhD Proposal and Defense

After passing the qualifying examination, the student must prepare a written thesis proposal and present it formally to the student's thesis committee and other interested faculty. Typically, the proposal will take place within 24 months of the student completing the qualifier.

The committee for the thesis proposal and defense will follow institutional requirements. Additionally, at least one committee member who is not the advisor must be robotics-affiliated faculty.

At the conclusion of the student's PhD program, the student must make a formal presentation and defense of their thesis research. A student must "pass" this defense to earn a PhD degree. Typically, the defense will take place within 24 months of the student completing the thesis proposal.

Robotics Course List

The Robotics courses are divided into four focus areas. Each focus area is comprised of core courses and electives, as detailed below. Beyond the courses in these four focus areas, there is also a list of additional Robotics electives.

Perception

Core Courses

ROBO513	ROBOT PROGRAMMING AND PERCEPTION	3.0
ROBO517	INTRODUCTION TO COMPUTER VISION	3.0
ROBO529	ESTIMATION THEORY AND KALMAN FILTERING	3.0
Elective Courses	\$	
CSCI508	ADVANCED TOPICS IN PERCEPTION AND COMPUTER VISION	3.0
Cognition		
Core Courses		
ROBO534	ROBOT PLANNING AND MANIPULATION	3.0
ROBO535	ADVANCED MACHINE LEARNING	3.0
Elective Courses	s - None.	
Action		
Core Courses		
MEGN544	ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL	3.0
ROBO550	MECHATRONICS	3.0
ROBO565	ADVANCED ROBOT CONTROL	3.0
ROBO567	THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS	3.0
Elective Courses	3	
EENG515	MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS	3.0

Interaction & Society

Core Courses

ROBO572	ROBOT ETHICS	3.0
ROBO576	HUMAN-ROBOT INTERACTION	3.0
Elective Course	es	
CSCI5XX	LINGUISTIC HUMAN-ROBOT INTERACTION	3.0
Additional Robo	tics Electives	
CSCI561	THEORY OF COMPUTATION	3.0
CSCI562	APPLIED ALGORITHMS AND DATA STRUCTURES	3.0
CSCI565	DISTRIBUTED SYSTEMS	3.0
CSCI572	COMPUTER NETWORKS II	3.0
EENG511	CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS	3.0
EENG521	NUMERICAL OPTIMIZATION	3.0
MEGN586	LINEAR OPTIMIZATION	3.0
MEGN587	NONLINEAR OPTIMIZATION	3.0
MEGN588	INTEGER OPTIMIZATION	3.0
MEGN686	ADVANCED LINEAR OPTIMIZATION	3.0
MEGN688	ADVANCED INTEGER OPTIMIZATION	3.0

ROBO513. ROBOT PROGRAMMING AND PERCEPTION. 3.0 Semester Hrs.

In this class students will learn the basics of integrated robot system programming and the design and use of algorithms for robot perception. Students will learn how to use the ROS robot middleware for the design of robot systems for perceiving and navigating the world; develop reinforcement learning based models for perception-informed autonomous navigation; and develop computational models for 3D robot perception and perceptual representation of human data. **Course Learning Outcomes**

- 1. Explain the basic concepts in human-centered robotics
- 2. Model and analyze human behaviors for human-robot interaction applications
- 3. Recognize the cutting-edge human-centered robotics research and applications
- 4. Apply the learned knowledge to other fields

ROBO517. INTRODUCTION TO COMPUTER VISION. 3.0 Semester Hrs.

(I) Computer vision is the process of using computers to acquire images, transform images, and extract symbolic descriptions from images. This course provides an introduction to this field, covering topics in image formation, feature extraction, location estimation, and object recognition. Design ability and hands-on projects will be emphasized, using popular software tools. The course will be of interest both to those who want to learn more about the subject and to those who just want to use computer imaging techniques. 3 hours lecture; 3 semester hours. Prerequisite: Undergraduate level knowledge of linear algebra, statistics, and a programming language.

Course Learning Outcomes

• 1. Be able to analyze and predict the behavior of image formation, transformation, and recognition algorithms

- 2. Be able to design, develop, and evaluate algorithms for specific applications
- 3. Be able to use software tools to implement computer vision algorithms
- 4. Communicate (in oral and written form) methods and results to a technical audience

ROB0529. ESTIMATION THEORY AND KALMAN FILTERING. 3.0 Semester Hrs.

Estimation theory considers the extraction of useful information from raw sensor measurements in the presence of signal uncertainty. Common applications include navigation, localization and mapping, but applications can be found in all fields where measurements are used. Mathematic descriptions of random signals and the response of linear systems are presented. The discrete-time Kalman Filter is introduced, and conditions for optimality are described. Implementation issues, performance prediction, and filter divergence are discussed. Adaptive estimation and nonlinear estimation are also covered. Contemporary applications will be utilized throughout the course. Offered Spring semester of odd years. 1.5 hours lecture; 1.5 hours other; 3 semester hours.

Course Learning Outcomes

- Use Bayes' rule to calculate a statistical inference. Given a description of a stochastic process, calculate the joint and conditional probabilities for this process.
- Using the appropriate algorithm, calculate the probability distribution function for the state of a dynamic system with stochastic inputs.
- "Build a model of a dynamic system that includes a probabilistic description of uncertain inputs.
- Design and implement an algorithm to estimate the internal states of a linear system with input signals that are Gaussian stochastic processes.
- Design and implement an algorithm to estimate the internal states of general systems with general stochastic inputs.

ROBO534. ROBOT PLANNING AND MANIPULATION. 3.0 Semester Hrs.

An introduction to planning in the context of robotics covering symbolic and motion planning approaches. Symbolic computation, symbolic domains, and efficient algorithms for symbolic planning; Robot kinematics, configuration spaces, and algorithms for motion planning. Applications of planning will focus on manipulation problems using robot arms.

Course Learning Outcomes

- 1 Implement algorithms for symbolic computation
- · 2 Construct symbolic planning domains for new scenarios
- 3 Implement algorithms for symbolic planning via constraint-solving and heuristic search
- 4 Implement algorithms for sampling-based motion planning
- · 5 Construct kinematic models of robot manipulators
- 6 Analyze planning algorithms for key properties: correctness, completeness, optimality
- 7 Evaluate the suitability of different planning approaches and apply appropriate algorithms to new planning scenarios
- 8 Communicate implementations, analysis, and evaluation in written and oral form

ROBO535. ADVANCED MACHINE LEARNING. 3.0 Semester Hrs.

Machine learning is the study of computer algorithms that improve automatically through experience. Machine learning systems do not have to be programmed by humans to solve a problem; instead, they essentially program themselves based on examples of how they should behave, or based on trial and error experience trying to solve the problem. This course aims at provide students with an understanding of the capabilities of machine learning (especially for deep learning due to its state-of-the-art performance for predicting and understanding data), and the knowledge to formulate the real-world problem to solve it effectively by a combination of computational idea motivations, learning theories, mathematical and optimization backgrounds/tools.

ROBO550. MECHATRONICS. 3.0 Semester Hrs.

A course focusing on implementation aspects of mechatronic and control systems. Significant lab component involving embedded C programming on a mechatronics teaching platform, called a haptic paddle, a single degree-of-freedom force-feedback joystick.

Course Learning Outcomes

- 1. Become proficient in mechanical system modeling, system identification and simulations.
- 2. Develop an understanding of how control theory is applied and implemented in practice.
- 3. Learn fundamentals of and how to use semiconductor devices in mechatronic systems
- 4. Learn the basics of sensor and actuator theory, design, and application
- 5. Gain experience in embedded C programming for mechatronic systems
- 6. Gain experience in research article reading and technical presentations

ROB0554. ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL. 3.0 Semester Hrs.

Mathematical representation of robot structures. Mechanical analysis including kinematics, dynamics, and design of robot manipulators. Representations for trajectories and path planning for robots. Fundamentals of robot control including, linear, nonlinear and force control methods. Introduction to off-line programming techniques and simulation. 3 hours lecture; 3 semester hours. Prerequisites: EENG307 and MEGN441.

ROBO565. ADVANCED ROBOT CONTROL. 3.0 Semester Hrs.

The goal of this course is to give the students an introduction to a fundamental working knowledge of the main techniques of intelligent learning-based control and their applications in robotics and autonomous systems. Specific topics include neural network based control, model predictive control, reinforcement learning based control, fuzzy logic control, and human-in-the-loop control.

ROBO567. THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS. 3.0 Semester Hrs.

This course will introduce and study the theory and design of multivariable and nonlinear control systems. Students will learn to design multivariable controllers that are both optimal and robust, using tools such as state space and transfer matrix models, nonlinear analysis, optimal estimator and controller design, and multi-loop controller synthesis. Offered Spring semester of even years. Prerequisite: EENG417. **Course Learning Outcomes**

• 1. define control-oriented problem statements for real-world problems,

- 2. model, analyze, and design controllers and estimators for singleinput, single-output (SISO) and multi-input, multi-output (MIMO) systems in time and frequency domains,
- 3. design optimal and robust controllers and estimators for these systems,
- 4. model, analyze, and design controllers for nonlinear systems,
- 5. explain the connection between state-space and transfer function representations of systems and the effects on controller design and analysis
- 6. model, analyze, and design feedback control systems using MATLAB and Simulink in both the time and frequency domains, and
- 7. understand and apply basic educational and learning theories and tools that will enhance your lifelong learning.

ROBO572. ROBOT ETHICS. 3.0 Semester Hrs.

(II) This course explores ethical issues arising in robotics and human-robot interaction through philosophical analysis, scientific experimentation, and algorithm design. Topics include case studies in lethal autonomous weapon systems, autonomous cars, and social robots, as well as higher-level concerns including economics, law, policy, and discrimination. Graduate enrollees will additionally participate in and report on the results of empirical and computational robot ethics research, with the goal of developing publishable works. **Course Learning Outcomes**

- 1 Understand the basic ethical theories, concepts, tools, and frameworks for analyzing the social and ethical ramifications of robotics
- 2 Be able to critically examine the ethical significance of the use of robotics in daily and technical fields including human-robot interaction, medicine, relationship, military, etc.
- 3 Develop a critical attitude toward the role of robotics in shaping human society including human perceptions and behaviors
- 4 Be able to use the theories, concepts, tools, and frameworks learned from this class to critically examine emerging robot ethics issues in the society.
- 5 Understand the tradeoffs underlying the design of autonomous moral agents.
- 6 Conduct robot ethics research grounded in both human-subject experimentation and algorithm development.

ROBO576. HUMAN-ROBOT INTERACTION. 3.0 Semester Hrs.

Human-Robot Interaction is an interdisciplinary field at the intersection of Computer Science, Robotics, Psychology, and Human Factors, that seeks to answer a broad set of questions about robots designed to interact with humans (e.g., assistive robots, educational robots, and service robots), such as: (1) How does human interaction with robots differ from interaction with other people? (2) How does the appearance and behavior of a robot change how humans perceive, trust, and interact with that robot? And (3) How can we design and program robots that are natural, trustworthy, and effective? Accordingly, In this course, students will learn (1) how to design interactive robots, (2) the algorithmic foundations of interactive robots; and (3) how to evaluate interactive robots. To achieve these learning objectives, students will read and present key papers from the HRI literature, complete an individual final project tailored to their unique interests and skillsets, and complete a group project in which they will design, pilot, and evaluate novel HRI experiments, with in-class time expected to be split between lecture by the instructor, presentations by students, and either collaborative active

learning activities or discussions with researchers in the field Prerequisite: Data Structures, Probability and Statistics or equivalent. Course Learning Outcomes

- Understand the theoretical foundations and critical application domains of human-robot interaction.
- Employ design techniques to design interactive robots.
- · Design human-subject experiments to evaluate interactive robots.
- Perform qualitative and quantitative analysis on the results of humanrobot interaction experiments.

ROBO598. SPECIAL TOPICS. 0-3 Semester Hr.

ROBO599. INDEPENDENT STUDY. 0.5-6 Semester Hr.

Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

ROBO599. INDEPENDENT STUDY. 1-6 Semester Hr.

ROBO707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.

Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.