Course of Study
for the Robotics Ph.D. Program

by the Faculty of the Ph.D. Program in Robotics

Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

Revised May 2008 and applied ongoing from August 2008

This document defines the degree requirements for students in the Ph.D. Program in Robotics at Carnegie Mellon. It is maintained by the Robotics Program Committee.

Table of Contents

Appendix

Overview of Doctoral Program

This document defines the degree requirements for students in the Ph.D. Program in Robotics at Carnegie Mellon. The program is designed so that a well-prepared student can complete the doctoral degree in four to five years. The program outline is:

- Course Qualifiers
- Research Qualifier
- Thesis

Parts 1 and 2, the qualification process, are concurrent and are designed to take approximately equal amounts of time during the student's first two years. Part 3, the thesis, will normally require two more years for completion. These requirements are detailed in this document.

The exact degree requirements for a student in the program are as defined in the Course of Study as of the date that student first enrolls in the Robotics Ph.D. Program. Any subsequent changes to the Course of Study may optionally be selected by the student, or the student may choose to retain the previous requirements.

Occasionally, it is appropriate for a student to deviate slightly from the requirements as defined in the Course of Study. A student may request approval for a specific proposed alternative from the Chair of the Robotics Ph.D. Program. Generally, the Robotics Program Committee will review the request and make a recommendation to the Chairperson.

The Robotics Doctoral Program sometimes accepts strongly motivated and exceptionally talented students from a wide range of educational backgrounds. It is each student's personal responsibility to arrive with, or to acquire rapidly thereafter, basic understanding (at the level of an introductory undergraduate course) in the following areas:

- Mathematics: calculus, linear algebra, numerical analysis, probability and statistics
- Computer Science: programming, data structures, algorithms
- Physics and Engineering: mechanics, dynamics, electricity and magnetism, optics

On request, the faculty will advise incoming students about individually appropriate alternative ways to satisfy these requirements, e.g., taking an undergraduate course, serving as a TA in an undergraduate course, or self-study by guided reading and discussion.

1. Course Qualifiers

Each student must complete the following set of course qualifiers:

- Four Core Courses, consisting of one course from each Core Area
- A Specialized Qualifier comprising 48 units of elective coursework (typically four graduate courses)

All courses must be passed with a grade of B-, or better.

The total amount of time required for a student to pass these qualifiers is expected to be approximately 50% effort for two years. Any student who does not complete them all by the end of the third year of study is no longer in good standing in the Program, subject to the judgement of the faculty.

All of the requirements for courses and exams within the Robotics Ph.D. Program are contained in the Course Qualifiers. There are no other course or exam requirements for the Doctorate degree in Robotics. Students are encouraged to attend additional courses if they and their advisor agree it would be valuable, but such courses are not required for the Robotics degree and may be substituted for required courses only if approved by the Chair of the Robotics Program. Seminars without course numbers are also frequently valuable educational experiences, but generally do not count for course credit.

Students in the Robotics Ph.D. Program must register with the university for all courses taken as part of fulfilling the Course Qualifiers.

1.1. Core Courses

Students must pass a total of four Core Courses with a grade of B-, or better. Students must pass one course from each of the following four Core Areas:

- **Perception**: vision, image sensors, range data interpretation, tactile and force sensors, inertial guidance, and other sensors. Core courses in Perception are 16-720 Computer Vision, and 16-722 Sensing and Sensors. (course descriptions begin on page 10)

- **Cognition**: artificial intelligence for robotics, knowledge, representation, planning, task scheduling, and learning. Core courses in Cognition are 15-780 Graduate Artificial Intelligence, and 10-701 Machine Learning.

- **Action**: kinematics, dynamics, control, manipulation, and locomotion. Core courses in Action are 16-741 Mechanics of Manipulation, and 16-711 Kinematics, Dynamic Systems, and Control.

- **Math Foundations**: optimal estimation, differential geometry, computational geometry, and operations research. The one core course in this area is 16-811 Math Fundamentals for Robotics.

1.2 Specialized Qualifier

The specialized qualifier is a sequence of courses chosen by the student to enhance the Core Course subject matter. These courses must total at least 48 units of graduate coursework (the equivalent of four full-semester courses). In this way, the basic science component of the program is complemented by studies in engineering and other areas that keep pace with new developments in the area of robotics. The courses should have coherence in subject matter, and should be chosen to enhance, or be complementary to, the Core Course subject matter. The subject matter of the Specialized Qualifier may be directly related to the student's thesis research, but is not restricted to that topic.

The Specialized Qualifier must be approved by the Program Committee Chairperson prior to registering for the courses. An exception can be made for courses taken in the first semester of Ph.D. studies or at Carnegie Mellon prior to entering the Robotics Ph.D. program. Approval forms are available from the Program Coordinator's office. It is recommended that the Specialized Qualifier be designed in conjunction with the student's advisor.

1.3 Waivers

On the basis of previous related course work, students may apply to waive any course by completing a Waiver Request form available from the Program Coordinator. The Chair of the Program will then assign a suitable faculty member to handle the request, typically the course instructor. In some cases, the faculty may determine that a student has demonstrated significant knowledge of the research area, but not quite sufficient enough to waive the course requirement entirely. In such cases, the faculty may grant a conditional waiver, contingent upon additional work, such as successfully TAing the course, or completing some designated project. If a student disagrees with the outcome, he or she may petition the Program Chair or the Program Committee, through the Program Committee Chair, to review the case.

2. Research Qualifier

The Research Qualifier consists primarily of the student's research, approximately the first two years, and is normally done while the student is completing the Course Qualifiers. The primary component of the Research Qualifier is supervised research under the guidance of a faculty member who serves as the student's advisor. In addition, the research qualification process includes serving as a teaching assistant, writing a research paper, and presenting a technical talk.

To oversee this process, the student forms a Research Qualifier Committee consisting of three faculty members and one Robotics Ph.D. student who has completed his or her second year of study. The faculty members should include the student's advisor, one faculty member from the student's research area, and one faculty member from outside the area. Typically, the student's advisor will be the chairperson of the committee. Forms to verify completion of the parts of the Research Qualifier are available from the Program Coordinator, and must be filled out by the Research Qualifying Committee (with the exception of the Teaching Requirement, which must be filled out by the instructor of the course).

The total time required for a student to accomplish the research qualifier is expected to be approximately 50% effort for two years. Any student who does not complete the entire Research Qualifier by the end of the third year of study will no longer be in good standing in the Program, subject to the judgement of the faculty.

The Research Qualifier comprises four components:

- **Research Skills:** The ability to create, explore, refine, and test new ideas in robotics. Students are expected to demonstrate awareness of previous work in their area of research, depth of insight into the problem, creativity in approaching the problem, and substance of results obtained.

- **Speaking:** The ability to communicate in oral presentation. Students are expected to demonstrate the ability to present technical material to a technical audience clearly and succinctly. The presentation must be made at a venue open to the public. Ideally, the Research Qualifying Committee will be in attendance, but committee members may designate proxies to evaluate the presentation.

- **Writing:** The ability to communicate in technical writing. A student is expected to produce a conference-length, or longer, paper, in which he/she is the sole, or the primary, author plus a one page executive summary in which he/she is the sole author. The paper should demonstrate a style, organization and clarity that enables researchers in the field to comprehend the problem, method, and results of the research being written about. Students who have written papers prior to entering the Robotics Program may submit them for evaluation, provided they meet the above criteria.

- **Teaching:** The experience of teaching in a classroom environment. This includes demonstration of as many as possible of the following: lecturing, recitation instruction, homework and exam design, grading, office hours, curriculum design. Each student must serve as a teaching assistant (TA) in one course relevant to the Robotics Program. Allowable courses will be defined by the Chair of the Program. Students may arrange to serve as TA by contacting the Program Coordinator at the beginning of the semester before the semester in which the student will act as a TA. The student is not required to spend more than twenty hours, but is not prohibited from doing so. The instructor should provide feedback to the student concerning the quality of the student's teaching. The instructor should report to the Program Coordinator his or her evaluation of whether the student has carried out the TA activities successfully.

3. Thesis

Researching, writing and presenting a thesis is intended to occupy approximately two to three years of activity, with these specific parts:

1. The Thesis Proposal
2. The Dissertation
3. The Oral Defense of the Dissertation

The evaluation of all three of these steps must be performed by the Program faculty, as represented by the student's Thesis Committee. The committee will consist of at least four members: a minimum of three from Carnegie Mellon, at least two of whom must be faculty members in the Robotics Institute, and at least one qualified researcher who is external to Carnegie Mellon. The student's advisor is the chairperson of the Thesis Committee. The entire composition of the committee must be approved by the Chair of the Program before the Thesis Proposal is presented.

It is expected that the **Thesis Proposal** will require about half a year of productive research for its preparation. In the Thesis Proposal, the student is formally asking the faculty for permission to pursue a line of research leading to the Dissertation. To do this, the student must do the following:

- Describe a problem and its importance;
- Summarize and evaluate what previous work has been done by others to solve this problem;
- State what has been accomplished so far by the student and how and why it will lead to the solution, or partial solution, of the problem;
- Describe and state what the student intends to do to complete the dissertation and how long it is expected to take; and
- Tell what contributions it will make to the field of Robotics that merit awarding the degree of Ph.D.

The oral presentation of the proposal is made to the entire research community, including particularly the Thesis Committee. The Thesis Committee must then express approval to the Chair of the Program if the proposal is to be accepted.

The **Dissertation** itself is normally preceded by a year or more of research and writing after the proposal. The Dissertation is a scholarly document describing the problem, related work, the student's approach, the results and insights achieved, and the significance of the work. The written dissertation must be presented to the Thesis Committee for approval. When the committee gives preliminary approval, the **Oral Defense** can take place. At the Oral Defense, the committee and the entire community will have the opportunity to question the work critically. Finally, the Thesis Committee must decide whether to approve the thesis.

The faculty of the Robotics program and the local community must receive notice of all thesis presentations at least one week in advance. Therefore, students are required to provide the Program Coordinator with complete information, no less than ten days before the scheduled presentation, including: title, abstract, committee members, on-line location of thesis document and/or hard copy. The Program Coordinator will advertise theses presentations on appropriate on-line and physical venues.

A student will be certified for graduation and allowed to attend commencement ceremonies when the thesis is unanimously approved by his or her Thesis Committee and has been delivered to the Program Coordinator in final form, at which time the student will be awarded the degree of Doctorate of Philosophy in the field of Robotics.

4. The Robotics Immigration Course

The student's research education begins in the Robotics Immigration Course, which all Robotics students must attend at the beginning of their first semester in the program. The Robotics Immigration Course is a series of lectures, discussions, and demonstrations that familiarize the students with Carnegie Mellon and the Robotics Program, introduce the research projects and faculty within the Program and affiliated departments, and describe the computational and other resources available to students in the Program. The Robotics Immigration Course gives students an opportunity to learn what it means to conduct research and to get to know the faculty in the Robotics Program.

5. Advising and The Marriage Process

The student's advisor will be the faculty member who works most closely with that student. This is usually the most important factor in the student's research education, so choice of an advisor should be based on careful consideration. At the conclusion of the Robotics Immigration Course, students are assigned to faculty advisors by the Marriage Committee. The assignments are based on the preferences of the students and the faculty, subject also to the research agenda (and funding) of the faculty.

In order to make this an informed process, the assignments are made several weeks after the Robotics Immigration Course, giving an additional period of time for the new students to meet the faculty individually. Each new student should use this opportunity to talk to all the faculty whose research interests might overlap those of the student. In this way, the students can learn about all the available research areas and all the faculty, and the faculty can meet and talk with the students, before commitments are made. Students and faculty present their preferences for advisor/advisee pairings, and these preferences are used in matching students and advisors. After the Marriage process, each student begins guided research under supervision of the advisor.

The duties of the advisor include approving the student's selection of courses, mentoring the student in research, advising the student about their progress, providing research opportunities and facilities for the student, and reporting on the student's progress in the Black Friday review process.

It is possible for a student to change advisors with approval of the Chair of the Program. A student may request to switch to a new advisor, to add an additional co-advisor, or to remove a co-advisor. In this way, the student's changing perspectives and research focus can be accommodated by the program. Generally, the student should discuss such matters first with their current advisor(s), then make a tentative agreement with the new advisor(s), then finally request that the new plan be approved by the Chair of the Program. The Chair of the Program is available to help guide the student through this process if needed.

6. Review of Progress

At the end of each semester, the entire faculty of the Robotics Program meets to discuss the record and progress of all students in the Program (for historical reasons called "Black Friday"). The evaluation for each student is based on several factors:

- The student's status at the start of the semester, as expressed by the previous Black Friday evaluation;
- The student's accomplishments during this semester, as described by the student in a form submitted prior to the meeting, and summarized at the meeting by the student's advisor;
- The advisor's evaluation, expressed in the form of a draft of a Black Friday letter that the advisor proposes to be sent to the student;
- Input from other faculty who have had dealings with the student;
- Discussion by the faculty of all of the above factors at the Black Friday meeting, which may include modifications to the letter drafted by the advisor; and
- Final decision by the Chair of the Program based on the above discussion.

After the meeting, the Chair of the Program will send a letter of progress to each student, based on the recommendation of the faculty at the meeting. Through this mechanism, the faculty can report "satisfactory" or "unsatisfactory" progress, offer recommendations to the student and advisor, set specific progress goals that must be achieved, or, if necessary, terminate a student's participation in the program. The continuation or conditions of a student's funding may also be determined in the meeting, as described in the document "Robotics Graduate Student Handbook".

In general, termination will be preceded by at least one unsatisfactory evaluation. An explicit warning (called an "N-1 letter") will normally be given one semester before any decision to terminate a student's participation in the program.

In addition to the progress review, the Black Friday meeting and resultant letters provide an opportunity for the faculty to learn about and acknowledge the students' contributions in service to the Program and achievements such as research publications and awards. Matters of academic policy are frequently discussed at the Black Friday meeting as they arise in the discussion of individual students.

The Black Friday process ensures that each student's progress is reviewed by the entire faculty, and not only by the advisor. The Black Friday process involves a careful consideration by the faculty of each student's case. If the student wishes to appeal the decisions reflected in their Black Friday letter, the student should state their perspective in a request to the Chair of the Program to review the case again. The Chair will undertake such a review, in consultation with the faculty as appropriate, and issue a written response to the student. If the student is not satisfied with the Chair's response, it may be appealed as described in the Student Handbook for Carnegie Mellon University.

7. Master's Degree in Robotics

The Robotics Doctoral Program at Carnegie Mellon is principally a Ph.D. program. However a student who is working towards a Ph.D. may receive the degree of M.S. in Robotics upon request by the student and upon completion of the following requirements:

- Four Core Courses from the Course Qualifiers
- 24 units of coursework from the student's approved Specialized Qualifier
- The Writing and Speaking portions of the Research Qualifier.

Thus a student will generally become eligible for the Master's degree only after two to three years of dedicated study. A Master's degree will be awarded to students following completion of all the requirements.

A. The Core Courses

A.1. The Perception Core Courses

- **16-720: Computer Vision**. Topics covered include image formation and representation, camera geometry and calibration, multi-scale analysis, segmentation, contour and region analysis, energy-based techniques, reconstruction of based on stereo, shading and motion, 3-D surface representation and projection, and analysis and recognition of objects and scenes using statistical and model-based techniques.

- **16-722: Sensing and Sensor.** The principles and practices of quantitative perception (sensing) illustrated by the devices and algorithms (sensors) that implement them. Learn to critically examine the sensing requirements of proposed applications of robotics to real problems, to specify the required sensor characteristics, to analyze whether these specifications can be realized even in principle, to compare what can be realized in principle to what can actually be purchased, to understand the engineering factors that account for the discrepancies, and to design transducing, digitizing, and computing systems that come tolerably close to realizing the actual capabilities of available sensors.

A.2. The Cognition Core Courses

- **15-780: Graduate Artificial Intelligence.** Introduction to Artificial Intelligence tailored toward the algorithms and applications of robotics, manufacturing, and engineering disciplines. Strong focus on modern numerical approaches to AI and robotics, including Bayes nets, classical decision-theoretical problems such as scheduling, and optimal and learning control of Markov systems. Motion planning and spatial reasoning, neural nets, qualitative reasoning, and fuzzy logic are covered in detail.

- **10-701: Machine Learning**. Machine Learning is concerned with computer programs that automatically improve their performance through experience. This course covers the theory and practice of machine learning from a variety of perspectives. Topics covered include learning decision trees, neural network learning, statistical learning methods, genetic algorithms, Bayesian learning methods, explanation-based learning, and reinforcement learning. The course covers theoretical concepts such as inductive bias, the PAC and Mistake-bound learning frameworks, minimum description length principle, and Occam's Razor. Programming assignments include hands-on experiments with various learning algorithms. Typical assignments include neural network learning for face recognition, and decision tree learning from databases of credit records.

A.3. The Action Core Courses

- **16-711: Kinematics, Dynamic Systems, and Conrol.** Basic concepts and tools for the analysis, design, and control of robotic mechanisms. Topics covered include foundations of kinematics, kinematics of robotic mechanisms, review of basic systems theory, control of dynamical systems. Advanced topics will vary from year, including motion planning and collision avoidance, adaptive control,and hybrid control.

- **16-741: Mechanics of Manipulation**. Kinematics, statics, and dynamics of robotic manipulator's interaction with a task, focusing on intelligent use of kinematic constraint, gravity, and frictional forces. Automatic planning based on mechanics. Application examples drawn from manufacturing and other domains.

A.4. The Math Foundations Core Course

- **16-811: Mathematical Fundamentals for Robotics**. This course covers selected topics in applied mathematics. Topics covered in the past have included: polynomial interpolation and approximation; solution of nonlinear equations; roots of polynomials; approximation by orthogonal functions such as Fourier series; optimization; calculus of variations; probability; numerical solution of differential equations.

B. The Research Qualifier

Some students may feel unprepared for the Research Qualifier. To help in that regard, there are courses and materials available that can prepare the student for speaking, writing, and teaching. For international students, the Intercultural Communication Center can recommend remedial course work and ICC workshops and seminars on an individual basis to help ensure that students have the language skills to pass these three portions of the Research Qualifier.

B.1. Research Skills.

This is the most important skill learned as a Ph.D. student, and it is the primary responsibility of the advisor is to mentor the student in research skills.

B.2. Speaking

A suitable course for a student to take to improve speaking ability is:

90-718: Professional Speaking (6 units)

In addition, the School of Computer Science has many videotapes of distinguished lecturers that are available for students to review.

B.3. Writing

A suitable course for a student to take to improve writing skill is:

76-369 Technical Writing for Engineers (9 units)

In addition, it is recommended that students read extensively in the field, especially award-winning papers, to get an idea of what good writing entails. Many papers and presentations exist on techniques for writing well, including Marc Raibert's "Good Writing". A student's advisor can also provide opportunities to review papers for conferences and journals, another helpful tool in improving a student's writing skills.

B.4. Teaching (Non-Native Speakers of English)

There are many courses and seminars offered weekly and each semester through the Eberly Center that can be taken to improve teaching ability.

For non-native speakers of English, Carnegie Mellon policy, in accordance with the Pennsylvania English Fluency in Higher Education Act, requires that all students be tested by the Intercultural Communication Center (ICC) before they can be certified to serve as International TAs (ITAs). The ITA test is offered several times during the year. A rating of "Category 2" or "Category 1" must be attained in order to qualify for certification. Students with Category 2 status are permitted to teach, but they must continue to take language training with the ICC during their teaching semester.

While Carnegie Mellon and Commonwealth of Pennsylvania policies only require the above standards of students TAing undergraduate courses, we in Robotics require these standards of all students TAing any Robotics course, and all Robotics students TAing a course in Robotics or any other department. This holds for both graduate and undergraduate courses. The Program Coordinator will monitor the status of all international students to ensure that a Category 1 or 2 has been attained before any student will be permitted to TA. Category 2 students will be monitored throughout the teaching semester to ensure that they are continuing with required training. Students found to be out of status, either by TAing before they have attained a Category 1 or 2, or by not continuing the required tutoring during the teaching semester, will risk not having the TA assignment count toward his or her Research Qualifier and having to TA again once the required standards are met.