AC 2009-671: BRIDGING THEORY AND PRACTICE IN A SENIOR-LEVEL ROBOTICS COURSE FOR MECHANICAL AND ELECTRICAL ENGINEERS

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Bridging Theory and Practice in a Senior Level Robotics Course for Mechanical and Electrical Engineers

Abstract
As a diverse discipline, robotics is a synthesis of a variety of subjects such as kinematics, dynamics, controls, mechatronics, mechanical design, artificial intelligence etc. The crossover of multiple areas makes the instruction of robotics courses a challenging task. Traditional robotics courses in mechanical and electrical engineering mainly focus on the analysis and modeling of classical robotic systems such as a two-to-six degrees of freedom robotic manipulator arm or a simple wheeled mobile robot. However, as more and more new branches of robotics are emerging in recent years (nanorobotics, biology-inspired robots and so on), it has become clear that materials covered in traditional robotics courses are not sufficient for students to solve new problems or create new robotic systems. It is therefore imperative that robotics courses be updated, and in many cases, redesigned to account for new branches of robotics that call on students to be competent in the theoretical underpinnings and also have the skills and confidence to apply these to real applications demanded by current practice. This paper first introduces the importance of robotics courses in the curricula of engineering programs, followed by results of a survey that reports on the features of robotics courses in several universities in the United States. The difficulties of designing a robotics course are then addressed. Finally, a suggested structure of a senior level robotics course is proposed.

Introduction

In the year of 2005, the Robotics Education Workshop took place in Robotics Systems and Science symposium at Massachusetts Institute of Technology (MIT)[1]. The main goal of this workshop was to discuss how to turn robotics into a core course that could be taught in every accredited Mechanical Engineering (ME), Electrical Engineering (EE), Computer Science (CS) undergraduate and graduate program in the United States, indeed, all over the world. Over 30 robotics professors from universities and institutes in the US, Europe, and Asia participated in this discussion and they all believed that it was a good time to start considering in which ways robotics could be taught broadly and then, determine and implement corresponding actions. The opinions of these professors were mostly due to the computing revolution and recent advances in actuators and sensors, which make it possible that today's personal computers (PCs) could become tomorrow's personal robots (PRs). Actually, the importance of robot-related projects in engineering curricula had already been well recognized by educationists[2], especially as a tool in the early stage of engineering programs to foster students' motivation and provide engineering design-oriented experience.

Currently, complete robotics curricula are only available at a few US universities or institutes with expertise in robotics research, such as University of Pennsylvania (UPenn), Carnegie Mellon University (CMU) and so on. At UPenn or CMU, by taking robotics and robotics-related courses, graduate students can fulfill the requirements on course hours towards their doctoral degrees[3,4]. Most recently, UPenn announced a master's degree in robotics[5]. However, in other institutions, robotics courses and robotics curricula are still difficult to design because of the imbalance between ME, EE and CS topics, the lack of low cost teaching platforms and labs, etc..

Before analyzing the collected examples of robotics courses from different universities and institutes, two important characteristics of robotics should first be addressed.

1. Robotics is a synthesis of a variety ME, EE and CS subjects. There is not a unified classification of these subjects. In this paper, the subjects are generally divided into two groups for convenience. First, *Robotics Science*. This group mainly includes the theories upon which robots are analyzed, such as kinematics, dynamics, control theory, optimization theory, artificial intelligence and so on. The second group is *Robotics System*, which mainly includes the key technologies used to implement the results of theoretical analysis, such as hardware design of robots, actuators, sensors, controllers, materials, electronics, software architecture and so on. Since so many subjects are involved in robotics, it is not surprising that by taking different tracks, more than two introductory robotics courses without any overlap could be proposed.
2. Robotics can greatly foster students' innovations and creativity. The value of robots projects in the early stage of engineering programs mainly lies on the understanding of design process. The theoretical analysis could possibly be none and the building of robots could just be based on Lego® kits. However, during this process, students are putting their creative solutions into reality. Since the robotics itself and most recent emerging new branches such as humanoid robots, nanorobotics, biology-inspired robots, all originated from creative ideas, there is no reason higher-level robotics courses should ignore the innovative elements in design.

In the following sections, the main objective of this paper is first stated, followed by an analysis of the results from a survey conducted over twelve syllabi from different universities. The potential challenges for students when taking robotics courses are also investigated and the suggestion for instructors in course design and delivery are addressed. Finally, a suggested structure of senior/graduate level introductory robotics courses in ME or EE departments is presented. The authors also put forward a robotics curriculum, including an outline with the connections between different robotics courses.

Objectives

The main objective of this paper is to combine knowledge of engineering education (effective approaches for student engagement and learning) with the authors' experiences in robotics research to design a senior/graduate level robotics course. In recent years, as a new course in ME and EE programs, robotics is playing more and more of an important role, for instance, its role in drawing students into these programs and motivating interests in cutting-edge research areas. The design of such a course is a challenging task, which usually calls on continuous update due to students' interests and newly emerging branches of robotics. The design process and considerations of such a robotics course, as an addition to the existing ME and EE curricula at Virginia Tech, are presented in this paper, including a suggested syllabus.

Robotics Syllabi Survey

This survey was conducted on a variety of twelve syllabi collected from different universities and institutes in the United States, Switzerland and Singapore. The documents of these courses were obtained from MIT OpenCourseWare (http://ocw.mit.edu), IEEE Robotics Course Ware (http://www.roboticscourseware.org*)* and the authors' personal correspondence with some instructors. The selected universities and institutes for the survey range from prestigious Ivy League universities, famous research universities with expertise in robotics, advanced research institutions, to well-recognized teaching universities. These syllabi were all developed between 2003 and 2008, thus allowing the survey to be focused on the most current robotics courses. The basic information of the twelve samples is listed in Table 1 below:

Table 1: List of the surveyed robotics courses
(SU: Senior Undergraduate; G: Graduate; AG: Advance Graduate)

	Course No.	*Course Name*	*Instructors*	*Department*	*University or Institute*	*Level*
1	*EML 6281*	*Robot Geometry I*	*Dr. Carl Crane*	*Mechanical and Aerospace Engineering*	*University of Florida*	*G*
2	*16-711*	*Kinematics, Dynamic System and Control*	*Dr. Chris Atkeson*	*Robotics Institute*	*Carnegie Mellon University*	*G*
3	*MEAM 620*	*Advanced Robotics*	*Dr. Vijay Kumar, et al.*	*Mechanical Engineering and Applied Mechanics*	*University of Pennsylvania*	*AG*
4	*EML 6834*	*Dynamics and Control of Robots*	*Dr. Gloria Wiens*	*Mechanical and Aerospace Engineering*	*University of Florida*	*G*
5	*ES 159/259*	*Introduction to Robotics*	*Dr. Robert Wood*	*Engineering and Applied Science*	*Harvard University*	*G/SU*
6	*N/A*	*Introduction to Mobile Robotics*	*Dr. Roland Siegwart*	*Institute of Robotics and Intelligent Systems*	*Swiss Federal Institute of Technology*	*G*
7	*CS 5247*	*Motion Planning and Application*	*Dr. David Hsu*	*Computer Science*	*National University of Singapore*	*G*
8	*CSAIL 6141*	*Robotics: Science and Systems*	*Dr. Daniela Rus, et al.*	*Electrical Engineering and Computer Science*	*Massachusetts Institute of Technology*	*G*
9	*CS 495/596*	*Software for Intelligent Robots*	*Dr Lynne Parker*	*Electrical Engineering and Computer Science*	*University of Tenessee*	*G/SU*

10	*ME 8204*	*Robotics: Analysis and Control*	*Dr. Hashem Ashrafiuon*	*Mechanical Engineering*	*Villanova University*	*G*
11	*ME 4524/ECE 4704*	*Robotics and Automation*	*Dr. Daniel Stilwell*	*Electrical and Computer Engineering*	*Virginia Tech*	*SU*
12	*2.12*	*Introduction to Robotics*	*Dr. Harry Asada*	*Mechanical Engineering*	*Massachusetts Institute of Technology*	*SU*

Discussion Points:
In the analysis below of Table 1 listing the syllabi, the terms "Course 1" to "Course 12" are used to conveniently refer to the twelve survey samples.

1. Department and Course Number:
   Among the twelve samples, the departments or institutions that offer robotics courses are mainly ME, EE and CS. Usually, most students that choose and take robotics come from these three departments. In some instances, a particular robotics course that is offered in more than one department can have different course numbers in ME and EE respectively. This is the case for Course 11.

2. Courses Levels:
   In the sample of courses listed in Table 1, "SU" stands for senior undergraduate level, with "G" for graduate level and "AG" for advanced graduate level. There are two undergraduate courses, seven graduate courses, and one advanced graduate course in the table. It is interesting to notice that Course 5 and 9 have both an undergraduate course number and a graduate course number. Therefore, the level of these two courses is denoted with "G/SU". In such courses, both undergraduate and graduate students will receive the same lectures, but the instructors' requirements on their assignments, labs, projects and exams are different.

3. Prerequisites:
   For the departments that are able to provide both graduate and senior undergraduate robotics courses, the senior course is typically a prerequisite for the graduate course. Almost all robotics courses set mathematics and computer programming as prerequisites. Since most ME, EE and CS departments can provide engineering-oriented courses on applied mathematics, instructors would like to use these as the prerequisites to robotics courses, such as Courses 3, 5, 9, 10, and 12. The pre-required knowledge of mathematics mainly includes calculus, vector analysis and differential equations. Depending on the focus of instruction, some courses may require fundamental knowledge on probability,

dynamics, optimization, control etc. In order to verify the theories in robotics science or conduct tests on actual hardware, most courses require students to be competent in programming. Students must understand at least one technical programming language, such as C/C++ or a numerical computing language such as Matlab, Mathematica and so on.

4. Textbooks:
   There is no unified robotics course syllabus; correspondingly, the unified textbook does not exist either. Depending on the coverage of material, instructors usually choose one book as the textbook to teach the fundamentals and use suggested reference books or the instructors' own notes to deliver advanced topics. The instructors of Courses 1, 6 and 12 use the books they authored as the textbooks, but they also provide other references. Among all the courses listed in Table 1, one textbook (first and later editions) received the greatest popularity, being chosen as the textbook by at least three instructors. This textbook is:

   Spong, M.W. and M. Vidyasagar, *Robot Dynamics and Control*. 1989, John Wiley & Sons, Inc.

   and its latest version:
   Spong, M.W., Hutchinson, S., and M. Vidyasagar, *Robot Modeling and Control*. 2006, John Wiley & Sons, Inc.

   This textbook sufficiently discusses the fundamentals of rigid body coordinates transformations, formulation of kinematics, dynamics and nonlinear controllers of serial robotic manipulators with two-to-six degrees of freedom. Due to the significant advances in vision sensors in past decades, the introduction to robotics vision and vision-based control are also included in the 2006 version of this book. In the latest version, the authors also outlined two possible course structures in the preface section, which is an important reference source for beginning instructors when designing robotics courses.

   Besides the book discussed above, other suggested reference books include:

   H.Asada and J-J.Slotine, *Robot Analysis and Control*, 1986
   J.Craig, *Introduction to Robotics: Mechanics and Control*, 1986
   M.T.Mason, *Mechanics of Robotic Manipulation*, 2001
   R.M. Murray, Z.Li, and S.S. Sastry, *A Mathematical Introduction to Robotics*, 1994
   Lorenzo Sciavicco and Bruno Siciliano, *Modeling and Control of Robot Manipulators,* Second Edition, 2000

   All of these textbooks can be treated as "robotics foundation" books because the fundamental mathematic backgrounds of robotics are intensively addressed. As for specialized topics in robotics, the following books are suggested for use by course instructors listed in Table 1:

Mobile robots:
R.Siegwart and I.R.Nourbakhsh, *Introduction to Autonomous Mobile Robots*, 2004
A. K. Peters *Mobile Robots, Inspiration to Implementation*
Dudek and Jekin, *Computational Principles of Mobile Robotics*,

Parallel robots:
L-W. Tsai, *Robot Analysis: The Mechanics of Serial and Parallel Manipulators*, 1999
J.P. Merlet, *Parallel Robot*, 2000

Robot motion planning:
LaValle, S., *Planning Algorithms*. 2006
J.C. Latombe. *Robot Motion Planning.* 1991
H. Choset, K. M. Lynch, S. Hutchinson, G. Kantor, W. Burgard, L. E. Kavraki, and S. Thrun. *Principles of Robot Motion : Theory, Algorithms, and Implementations.* 2005.

Artificial Intelligence:
Russel & Norvig, *Artificial Intelligence, A Modern Approach*
Robin Murphy*, Introduction to AI Robotics*, 2000.

Materials such as academic journals and magazines can serve as complementary resources to textbooks and reference books, especially when covering advanced topics. These suggested materials include:

IEEE Robotics & Automation Magazine
*IEEE Transactions on Robotics (*previously *IEEE Transactions on Robotics and Automation)*
International Journal of Robotics Research
Journal of Robotic Systems
Robotica
ASME Journal of Mechanical Design
ASME Journal of Mechanisms and Robotics

5. Coverage of Topics and Robot Subject

Regarding instructors' coverage on robotics topics, the twelve sample courses in Table 1 can be generally divided into groups.

The first group of courses is mainly offered in ME/EE departments, such as Course 1, 4, 5, 10 and 11. The instructors in this group prefer to use serial robotic manipulators as the subject to study the fundamentals of robotics. Topics of these courses include the fundamental coordinate transformation of rigid bodies, kinematics and dynamics modeling. The specialized or advanced topics could cover nonlinear control, motion planning, implement and design of hardware, software architecture and so on, depending on the expertise of the instructors and the departments. In some of these courses, robots other than serial robot manipulators such as legged robots, parallel robots, surgical robots are briefly introduced.

In contrast with the aforementioned group of courses, the second group of robotics courses is mainly offered in CS departments, such as Course 6, 7, 9. These courses focus more on the intelligent programming of wheeled mobile robots. Instead of carrying out the kinematic and dynamic modeling of robots, these courses intensively study the navigation of such mobile robots, including the path planning, machine learning, reasoning, localization, mapping, human-robot interaction and so on.

Institutions with strong background in robotics research can accommodate both robotic manipulators and mobile robots in one course, such as Course 2, 3, 8 and 12. It is notable that, in the third group of such robotics courses, the hardware-based labs and projects are also provided. Students can develop their projects ranging from industrial robots, walking machines to multiple wheeled robots.

6. Labs and Projects:
   Currently, robotics resources are concentrated at a few institutions. Because of the high cost of robot electronics, not every university can offer robotics courses with labs and hardware-based projects. Low cost experimental robots and robot prototyping are also an active area in robotics research. The lab in Course 5 of Table 1 provides a paradigm in robotics lab. The detailed information can be found in Reference 7. An industrial robot, Catalyst-5 from the Thermo Electron Corporation, is used as the platform for students' labs and course projects. Forward and inverse kinematics, velocity kinematics and singularity, path planning and obstacle avoidance, vision control and manipulation are carried out on this robotic manipulator. In the process of the project, students must correctly implement the first module before implementing the next one. This is also an interesting characteristic of robotics fundamentals. Notable labs and projects from other courses in Table 1 include the programming of mobile robots for cooperative operation, the manipulation of objects based on vision control and the design of the walking gaits of legged robots. Some of these projects have great value in both education and research.

7. Course Hours:
   All robotics courses in Table 1 are typical 3-credit courses, which take 2.5 hours to 3 hours per week. The courses with labs usually take longer than 3 hours per week.

8. Grading Policies:

   The grading of these course samples is comprehensive. It is usually based on exams, homework, labs, quizzes and projects. A few instructors have requirements on students' participation. Both open book exams and close book exams are used by the instructors and the course project often involves a written deliverable and an oral presentation.

Considerations for Students and Suggestions for Instructors

The complication of robotics courses renders difficulties to both students and instructors. Some considerations for students are investigated in this section, followed by suggestions to the instructors.

Considerations for students:

1. Prerequisites:

   The prerequisites of robotics courses emphasize a lot of mathematics background. As the lectures proceed, the instructors could briefly review the knowledge of some concepts, but the students would be better to understand them before taking the course.
2. Students' interests and the actual course materials:

   Not every student is familiar with the content of robotics courses. Some students might expect to design a highly intelligent humanoid robot that can walk and talk. However, they probably will end up spending a lot of time with vector operations and differential equations. The possible frustration and disappointment received are bad for fostering students' interests in robots. The instructors would be better to introduce the current trends of robotics to students and use the early stage of computers as an analog.
3. Interactions between different disciplines:

   As the introductory section of this paper points out, robotics is an integration of various ME, EE, CS subjects. It is expected that students taking robotics courses are from different backgrounds. Although they might already have background in kinematics, dynamics and control theory, due to the novelty of robots, the way those theories are treated and applied in robotics are slightly different from the classical ways through which kinematics, dynamics or control systems are delivered. Instructors should utilize these classical theories and carefully guide students through the whole process. Thus, both students' understanding on novel robots and their previous backgrounds could be strengthened.

Suggestions for instructors:

1. Grasp the insight of robotics:

   Inherently, most instructors of traditional robotics courses believe that a sound foundation on mathematic and physical principles is the way that leads to the mastering of robotics. However, Piepmeier, J., et al., from United States Naval Academy proposed that besides knowledge and experience on robotics, the insight on robotics in a global context should also be addressed[8]. They use three approaches, robot news, multimedia facts and mass media function, to foster students' insight on robots. Some robotics courses have already adopted these interesting methods, such as Course 11 in Table 1.

2. Foster creativity in robotics courses:
   Since most robotics courses have high requirements on students' mathematic ability, the instructors are trying to deliver the analytical approaches to robotics problems to students in an intensive way. The importance of analytical and numerical tools in robotics analysis cannot be denied. However, the design innovations in robotics should also be emphasized. Most robotics concepts originated from initial creative ideas. For example, serial robotic manipulators come from industrial assembly lines; parallel robotic manipulators come from the motion simulation of aircraft; humanoid robots come from people's dream that robots can behave like humans beings and serve humankind. Further, robots with novel locomotion are often inspired by biology. Such examples are countless. The complex nature of these novel robotic systems raises them to the level of academics, but creativity is still the keystone. Therefore, it is suggested the instructors not only assign problem-solving-oriented projects, but also give students the freedom to consider the design of their own robots, which could possibly become new branches of robotics in the future.

3. Balance robotics lab, prototyping and simulation:
   In robotics courses, computer simulation is usually used as a tool to verify the results of theoretical analysis. It is of low cost, and easy to implement after sufficient training. With graphics functions, the results can be displayed in an intuitive way through friendly interfaces. Almost all robotics courses require students to be competent in writing simulation codes. Nevertheless, simulations cannot completely substitute the functions of physical models, especially when the lectures, labs, or projects call on students' ability in hardware operation, i.e., the design and fabrication of robot prototypes. In an institution where robot resources are not adequate for scores of students to take labs, the instructor can rely on simulations to deliver the fundamental knowledge of robotics. As the courses evolve in practice, the instructors should consider the purchase of robotic manipulators and mobile robots, or the construction of novel robot prototypes to complement the theoretical concepts delivered in the lectures. The development of low cost robot prototypes based on model kits can serve both education and research positively. An example can be found in Reference 6, where a six degrees of freedom parallel manipulator prototype, usually the subject of robot kinematics research, is built with Lego® kits.

Proposed Syllabus for a Senior/Graduate Level Introductory Robotics Course

Based on the analysis conducted in previous sections, a proposed syllabus is presented for a senior/graduate level introductory robotics course in the ME department of Virginia Tech (see Appendix A). This course now has been approved as a special-study course and is open to both seniors and graduates students. Depending on the backgrounds of actual senior and graduate students, the requirements of the course objectives could be slightly different, as the case in Course 5 in Table 1.

The textbook of this course is the latest version of *Robot Modeling and Control.* Additional readings also come from complementary reference books, journals and magazines. The requirements on mathematics and programming are specified. The learning objectives and associated topics and materials are listed. The introductory topics include fundamental coordinate transformations, kinematics and trajectory planning. Based on the instructors' expertise, the kinematics of mobile robots and parallel robots are delivered as advanced topics. The course will also briefly cover the emerging new branches of robotics. Faculty members with expertise and specialization in these areas will be invited to give guest lectures.

The grade of this course is based on exams, assignments, projects and a presentation. In-class quizzes are used to test students' understanding on the knowledge just covered. Each student is required to lead a 5-minute discussion on most recent robot news. This discussion is also counted as a quiz. The scores of the quizzes are mainly used to raise the students' percentage grades near the borderline of lettered grades. The presentation gives students an opportunity to consider the design of their own robots. Students are expected to illustrate the concept of their robots in a concise way. They are not required to perform in-depth analysis and present the results. Instead, they must establish well the big picture of the research and the development scope. The challenges in the novel robots will be described and students are required to consider how the knowledge learnt in this course can be synthesized to solve emerging problems.

Proposed Robotics Curriculum

The structure of an initial robotics curriculum is presented in this section. The structure is organized in a hierarchical manner from senior robotics course and projects to advanced graduate robotics courses.

Senior Robotics Course:
Introduction to Robotics
Capstone Senior Design Projects, Robots-related

Note: The capstone senior design projects on robot development can be used to apply the knowledge in introductory robotics course

Entry Graduate Robotics Course:
Robotics Kinematics, Dynamics and Control

Note: This graduate course can also be used to recruit graduate students interested in robotics, but with different backgrounds. The requirements are higher than those of a senior level course. Such examples are shown in previous sections. The coverage can range from fundamental robotics theories to selected advanced topics.

Intermediate Graduate Robotics Courses:
Introduction to Mobile Robots

Introduction to Parallel Robots
Robot Locomotion
Dynamics and Control of Autonomous Vehicles
Dynamics of Legged Robots and so on

Note: These courses serve as the continuation study of the advanced topics covered in Entry Graduate Robotics Course.

Complementary Courses:
Engineering Vibrations
Dynamics of Machinery
Nonlinear Control Theory
Digital Filtering
Machine Learning
Computer Vision and Graphics and so on

Note: These courses are selected from other areas but they can be used to further strengthen students' background in particular areas.

Advanced Graduate Robotics Courses:
Advanced Robotics
Advanced Robot Kinematics, Dynamics and Control

Note: These courses are oriented to graduate students interested in conducting advanced robotics research. Academic journal papers can be used as the references for students. It is possible to have multiple instructors, and each instructor is responsible for a particular area such as Course 3 in Table 1. The outcome of these courses could lead to high-quality research papers.

Conclusion and Future Work

As the result of the survey conducted on twelve examples, a syllabus of a graduate robotics course is presented, together with an initial robotics curriculum. Future work will include the refinement of learning objectives, the improvement of delivery strategy and the evolution of the course through practice. The design of the labs will also be investigated.

Bibliography

1. Rus, D., "Teaching Robotics Everywhere," IEEE Robotics & Automation Magazine, March, 2006
2. Heywood, J., Engineering Education : Research and Development in Curriculum and Instruction, Wiley-IEEE Press, 2005
3. Course List, Robotics Institute, Carnegie Mellon University, http://www.ri.cmu.edu/ri_static_content.html?menu_id=276
4. Course List, GRASP, University of Pennsylvania, http://www.grasp.upenn.edu/education/index.html#grad
5. Master of Science in Robotics, http://www.grasp.upenn.edu/education/introduction.html
6. Ebert-Uphoff, I., "Introducing Parallel Manipulators Through Laboratory Experiments," IEEE Robotics & Automation Magazine, September, 2003
7. Wood, R., "Robotic Manipulation Using an Open-Architecture Industrial Arm: A Pedagogical Overview," IEEE

Robotics & Automation Magazine, September, 2008
8. Piepmeier, J., et al., "Modern Robotics Engineering Instruction," IEEE Robotics & Automation Magazine, June, 2003

Appendix A

Robot Modeling and Analysis

Level: Senior/Graduate

Course Description: This course covers both the fundamentals and the advanced topics in robotics, including homogeneous coordinate transformation, forward and inverse kinematics, Jacobian analysis, singularities, dynamics modeling, motion and path planning, and selected topics on joint control. Various types of industrial manipulators with serial or parallel configuration, and mobile robots with wheeled or legged locomotion, are utilized as examples to illustrate the principles of robot analysis. New emerging areas of robotics in recent years are briefly introduced

Textbooks:
Spong, M.W., Hutchinson, S., and M. Vidyasagar, *Robot Modeling and Control*. 2006, John Wiley & Sons, Inc.
and
L-W. Tsai, *Robot Analysis: The Mechanics of Serial and Parallel Manipulators*, 1999

Reference Books:
Spong, M.W. and M. Vidyasagar, *Robot Dynamics and Control*. 1989, John Wiley & Sons, Inc.
H.Asada and J-J.Slotine, *Robot Analysis and Control*, 1986
J.Craig, *Introduction to Robotics: Mechanics and Control*, 1986
R.Siegwart and I.R.Nourbakhsh, *Introduction to Autonomous Mobile Robots*, 2004
M.T.Mason, *Mechanics of Robotic Manipulation*, 2001
R.M. Murray, Z.Li, and S.S. Sastry, *A Mathematical Introduction to Robotics*, 1994

Reference Journals:
*IEEE Transactions on Robotics (*previously *IEEE Transactions on Robotics and Automation)*
International Journal of Robotics Research
Journal of Robotic Systems
Robotica
ASME Journal of Mechanical Design
ASME Journal of Mechanisms and Robotics

Prerequisites:
Basic knowledge of linear algebra, differential equations, matrix theory. Programming and simulation with MATLAB, Mathematica, etc.

Learning Objectives:
1. Knowledge of basic robotics concepts, research subjects and applications
2. Comprehension and application of coordinate formulation rules in robotic systems

3. Analyses on the kinematics and dynamics of representative robots
4. Development of simulation tools for robots on kinematic level
5. Design of novel robots

List of Topics:

Robot definitions and classifications

Basic concept in kinematics:

- Reference frames and rigid body representation
- Matrix representation of rotational and translational transformations

Forward kinematics of serial robotic manipulators:

- Denavit-Hartenberg Representation of rotation and translation
- *Exponential coordinates for rigid motion and twists
- *Screws: a geometric description of twists
- Position analysis
- Velocity and acceleration problems

Inverse kinematics of serial robotic manipulators:

- Inverse position analysis
- Geometric methods
- *General 6R problems

Instantaneous kinematics:

- Jacobian matrix
- Singularity conditions
- Inverse velocity and acceleration problems
- *Screw-based Jacobian matrix

Motion planning and trajectory generation

- Path planning using potential fields
- Trajectory planning

*Kinematics of wheeled robots

- Forward wheel kinematic models
- Wheeled robot kinematic constraints

*Kinematics of parallel robots

- Mobility analysis
- Forward and inverse kinematics
- Forward and inverse singularities
- Grassmann geometry

*Introduction to emerging research areas in robotics

- Biology inspired robots
- Humanoid robots and nanorobotics

*Advanced topics

Course Grading Policy:

1, Two exams, 40%
2, Assignments 25%
3. Simulation based project 25%
4. Presentation: the design of novel robotic systems 10%
5. In-class quiz ?%