Spring 2012 Syllabus

Class location and time: *Tuesdays and Thursdays 2:35-3:50 pm at Olin Hall 134.*

Instructor

Nabil Simaan
Office hours: Thursdays 16:00-18:00 or by appointment (615-343-0470 or nabil.simaan@vanderbilt.edu).

Course Mission

This course is for graduate students interested in theoretical kinematics and robot design and optimization. The course will cover preparatory topics for graduate research in robotics. We cover topics on parallel robots, serial robots, multi-fingered hands, robots with kinematic and actuation redundancies.

Course Requirements

The grading will be based on bi-weekly assignments, class participation, 1 term project and a project presentation. We will also assign several recent research papers for group and individual research study. Assignments will incorporate review of a relevant journal papers and partial reproduction/verification of their results. Other topics such as analysis of wire-actuated robots and grasp stability will be included as self-study assignments using the tools presented in class.

Individual projects will cover a research project on topics related to the course. Examples of such topics include: multi-fingered hand grasping, wire actuated robots, snake-like robots, direct kinematics of novel mechanisms, task-based optimization and analysis of mechanisms using dual numbers and quaternions, optimization and dexterity evaluation of redundant mechanisms.

6 bi-weekly assignments out of which 5 are mandatory ---------------------------------- 60%
1 term project -- 30%
1 term project presentation --- 10%

Textbooks

The course will mainly focus on the class notes of the instructor. Most of the topics covered are included in the following recommended text books. As an introductory course to graduate research in robotics the course will use relevant technical papers to cover some of the material. Reference [3] is the recommended text book that covers most of the material provided in class.

[1] ***Theoretical Kinematics*** *by* Bottema, O. and B. Roth: Dover Publications, Inc., 1979
[2] ***Kinematic Geometry of Mechanisms*****,** Hunt, K.: Clarendon Press, 1978
[3] ***Fundamentals of Robotic Mechanical Systems***, by Jorge Angeles, 2nd Edition (3rd edition is expected soon so check if it is available), Springer, 2003.
[4] ***Advanced Robotics***, by Yoshihiko Nakamura, Addison-Wesley Publishing Company, 1991 (this book is not in print anymore, but I will be providing some of my own notes based on this book.).
[5] ***A Mathematical Introduction to Robotic Manipulation,*** Murray, R., Zexiang Li, Sastry, S., 1994.
[6] ***Engineering Applications of Noncommutative Harmonic Analysis***, Chirikjian, G., Kyatkin, A., 2000.
[7] ***Ideals, Varieties, and Algorithms***, Cox, D., Springer, 1996.
[8] ***Using Algebraic Geometry,*** Cox, D.,: Springer, 1998.
[9] Sommese, A., Wampler, C. **The numerical Solution of Systems of Polynomials Arising in Engineering and Science, , 2005**
[10] Simaan, N., ***Analysis and Synthesis of Parallel Robots for Medical Applications***, M.Sc. thesis, Technion,Mechanical Engineering, Haifa, Israel, 1999 (available at http://research.vuse.vanderbilt.edu/arma/people/nabil_simaan/ms_research.shtml)
[11] Simaan, N. **Task-Based Design and Synthesis of Variable Geometry Parallel Robots**, Ph.D. Dissertation, Technion, Mechanical Engineering, Haifa, Israel, 2002 (available at http://research.vuse.vanderbilt.edu/arma/people/nabil_simaan/phd_research.shtml).
[12] Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace and Virtual Reality, J. B. Kuipers.
[13] Visualizing Quaternions, Andrew J. Hanson.

[14] Rotations, Quaternions, and Double Groups, Simon Altmann
[15] Robot Analysis, L.-W. Tsai
[16] Introduction to Theoretical Kinematics, J.-M. McCarthy
[17] Foundations of Robotics, T. Yoshikawa
[18] Dual-Number Methods in Kinematics, Statics and Dynamics, Ian Fischer
[19] Applications of Dual Numbers and Quaternion Algebra to Analysis of Spatial Mechanisms, A.-T. Yang.
[20] Solving Polynominal Systems Using Continuation for Engineering and Scientific Problems (Classics in Applied Mathematics), Alexander Morgan

Planned Course Schedule

Date	Subjects covered	Homework
Week 1	Introduction to the course and review of rigid body transformations (weeks 1-2): • Symmetry operations • Rotations as symmetry operations • Classification of symmetry operations • The trace of a general rotation matrix • Euler's theorem: geometric proof of Rodriguez	
Week 2	• Rodriguez vectorial formula for rotation • Finding the Rodriguez axis from two-point motion (three-point motion will be given in homework) • Angle-axis R(n, θ) parameterization of rotations • Composition of rotations using Rodriguez formula – analytic proof to Euler's theorem. • Active and passive rotation sequences using Rodriguez vectors • Cayley's formula • Relationship between Rodriguez and Cayley's formula • From Cayley's equation to the exponential product • Linear invariants and Euler Rodriguez parameters • Parameterizations of rotations: Gibbs/Rodriguez vectors, Linear invariants, Euler parameters, Axis-angle parameters, Euler angles	H1
Week 3	Special methods in kinematics: quaternions and rotation vectors, (time permitting we will expand this topic also in homework and projects). Examples: Inverse kinematics using rotation vectors.	
Week 4	Special methods in kinematics II: • representations of a screw. • Line and point transformations, Plucker coordinates of a line. • The screw and the screw transformation and the exponential representation of a screw transformation. • Cayley's formula for screw motion, • dual numbers • dual quaternions • Calculating the finite displacement screw for a specified motion of three points (to be given in HW). • Examples: Transformation verses displacement matrices: the *zero-reference method*	H2
Week 5	Introduction to line geometry: • homogeneous representation of points and lines • Plucker line coordinates • Line varieties in space	

Week 6	Introduction to screw methods in kinematics and robot design • Representation of a screw • Finding the line coordinates of a given screw • The reciprocity principle • Relationship between line geometry and reciprocity • Examples of simple mechanisms • The screw systems	H3
Week 7	Introduction to screw methods in kinematics and robot design Continued. Examples and relationship to mechanisms and robots. Simple planar parallel robots.	
Week 8	Instantaneous kinematics of open and closed kinematic chains • Mobility, connectivity, Grubler's formula and loop mobility criterion. • Input-output relationship in closed-loop mechanisms using auxiliary coordinates. • Derivation of the instantaneous kinematics Jacobian based on kinematic constraints • Geometric interpretation for serial and parallel robots • Applications of line geometry for singularity analysis	**Assignment of term projects** H4
Week 9	Kinetostatic analysis of serial and parallel robots • Alternative derivation if instantaneous kinematics Jacobian using statics and virtual work principle • Screw-based Jacobian • Stiffness mapping for parallel and serial robots • Series-parallel dualities • Performance measures: manipulability ellipsoid, stiffness ellipsoid, isotropy, condition number, JRAE)	
Week 10	Introduction to redundant manipulators • Singular value decomposition • Solutions of over determined and under-determined linear equations • Task-priority optimization • Obstacle avoidance, singularity avoidance • Actuation redundancy and optimization of joint efforts • Singularities of actuation redundancy (time permitting we will discuss my work on this topic) • Wire-actuated robots and stability analysis of muti-fingered hands (will be discussed briefly and covered in homework).	H5
Week 11	Introduction to numerical and symbolic methods for solution of direct and inverse kinematics problems • Homogenization of polynomials • Root counts for polynomial systems – Bezout and BKK bounds • Introduction to homotopy continuation methods	
Week 12	Introduction to numerical and symbolic methods for solution of direct and inverse kinematics problems - continued • Introduction to the theory of elimination: the Dialytic elimination method • The Sylvester and Bezout resultants, Dixon resultants, multi-homogeneous resultants (time permitting) • Transforming the resultant formulation to an associated generalized eigenvalue problem	H6
Week 13	**Research topics and presentations of student projects**	
Week 14	**Research topics and presentations of student projects**	
Week 15	**Research topics and presentations of student projects (9:00-11:00 ME conf room)**	