Electrical & Computer ENGINEERING

Carnegie Mellon

Course Syllabus

Biomedical Imaging & Analysis (J1-791)
Fall 2014

Instructor: Prahlad G Menon, PhD
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Office Hours: 3:00pm-4:00pm, on Tuesdays.

Teaching Assistant(s): -
Email Address: -
Office Hours: -

NOTE:

1) For email communication, please include *J1-791* in the subject line.
2) The responsibility of the TA (when assigned) will be limited to grading. The TA is not required to answer student questions. The course instructor will be responsible for answering all student questions.

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Course Description:

The goals of this course are to familiarize students with biological and medical imaging data from various imaging modalities (eg: Magnetic Resonance Imaging (MRI), X-ray Computed Tomography (CT), Fluoroscopy, Ultrasound and Optical Systems for Microscopy), how these data are acquired as well as how to process 2D, 3D and 4D (3D + time) data for quantification and visualization purposes using contemporary software tools and open-source libraries (including, SimpleITK, ITK, VTK). Additionally, this course integrates these image-processing concepts their real-world applications from the fields of mechanical and biomedical engineering, including computational simulation of mechanics or flow for improved medical diagnosis and treatment and image-guided surgery. Students will build a strong fundamental mathematical and programming background in regard to formulating and implementing complex image processing pipelines, while appreciating the nuances of the basic mathematical principles such as linear algebra, Fourier theory, statistics, machine learning etc. in the context of advanced signal processing settings. Major image-processing topics covered will include basic image filtering and de-noising, feature detection, medical and biological image segmentation, registration, shape characterization as well as biomarker extraction and

validation. Finally, the tools and techniques learned during this course will be applied by students at a systems level with the goal of building image-processing pipelines to solve a practical bioimaging problem through an independent project. At the end of the course, students will be equipped with theoretical and practical skills in medical image analysis and visualization, including skills relevant to general image processing such as quantification of data and classification.
Prerequisites: Basic vector calculus and linear algebra (or permission of the instructor), as well as a working knowledge of Matlab as well as either C++ or Python.

Number of Units: 12

Pre-requisites: Knowledge of vector calculus, basic linear algebra, C++ or Python programming skills and Matlab programming skills.

Class Schedule:

- **Lecture**:
  1:30 pm – 2:50 pm, Tuesdays & Thursdays.

Venue:

Week 1-4（Aug. 25~ Sep. 20）:
A103/A103，Teaching Building, SYSU East Campus

Week 5-16 (Sep. 21) :
D401/C302, Teaching Building, SYSU East Campus

Required Textbook(s):

1) ***Machine Vision****, by Wesley E. Snyder & Hairong Qi, © 2004, ISBN 978-0-521-16981-3 (paperback) or 978-0-521-83046-1 (hardback)*
2) ***Insight into Images****: Principles and Practice for Segmentation, Registration and Image Analysis, edited by Terry S. Yoo, © 2004, ISBN 1-56881-217-5*

Note*: Selected chapters from the above-mentioned textbooks will be made available to the enrolled students, as PDFs, via the course website on Blackboard.*

Other Supplemental Materials:
Supplemental reading assignments and additional material, including but not limited to code and instructional tutorials, will be uploaded for student access as the course progresses, via the course website on Blackboard.

Brief List of Topics Covered:

Course Blackboard: To access the course blackboard from an Andrew Machine, go to the login page at: http://www.cmu.edu/blackboard. You should check the course blackboard daily for announcements and handouts. PDF copies of lecture notes will also be available via the instructor's Teaching website, http://justcallharry.com/bia-fall-2014.html .

Course Wiki:
Students are encouraged to use the ECE wiki to provide feedback about the course at: http://wiki.ece.cmu.edu/index.php.

See tentative course schedule (below) for further detail…

Grading Algorithm:

Quizzes: 20%

- Not present / not taken = 0
- Your course grade is equally affected whether you miss 1 point on a 3 point quiz, or you miss 1 point on a 10 point quiz.
- Lowest two quiz scores are dropped (i.e. the 2 on which you missed the most points) in order to be accommodating in the event that you are missing for a week-long conference.

Homework: 30%

Final Project: 40%

- 15% presentation.
- 25% code.

Final Letter Grade
While lower cutoffs may be used based to relax the expectations based on principles of grading the class on a bell curve, the following maximum grade cutoffs are guaranteed:

- >= 93.5 A
- >= 90.0 A-
- >= 87.5 B+
- >= 83.5 B
- >= 80.0 B

Tentative Course Calendar

- 23 lectures, total + 10 Quizzes + 5 Homework Assignments + 1 Final Project.
- +2 classroom sessions for class project presentations.

Course Calendar

Date	Day	Class Activity
August		
26	Tue.	Blackboard Open – **Assignment #1** given: - Understand student backgrounds and motivation to study Biomedical Imaging and Image Analysis. - Basic Math & Programming – pre-class assignments. - Summary of imaging modalities + background reading on medical imaging modalities from PDFs uploaded.
September		

9	Tue.	CLASSES BEGIN. Lecture 1: Introductions, Purpose & Syllabus.
		
		Assignment #1 due:
		- Q&A – ungraded quiz on imaging modalities.
		
		Imaging Modalities and Medical Image Acquisition:
		- Magnetic Resonance Imaging
		    o What is s pulse sequence + example image datasets.
		- Computed Tomography
		    o Intro to tomographic image reconstruction
		    o Intro to Structure from Motion
		- Ultrasound – Examples of 2D and 3D trans-thoracic as well as trans-esophageal echocardiography.
		- Fluoroscopy
		    o Orthographic vs. Perspective Projection.
		- Anatomical Axes and standard views for Radiology or Interventional Radiology.

11	Thur.	Imaging Modalities and Medical Image Acquisition: - Light microscopy fundamentals & applications of fluorescence microscopy Medical Image processing software – a FDA regulated medical device: - Format of medical imaging exchange – DICOM and patient data privacy (HIPAA regulations). - Classes of FDA regulated medical devices. - Regulatory approval processes (i.e. FDA 510k clearance).
16	Tue.	Overview of biomedical and biological image processing and visualization libraries (including but not limited to ITK & VTK) and software. - Basics of image visualization: Volume rendering, Slicing, Clipping, Iso-surfaces, Iso-contours, etc. - Demo of SimpleITK, Python. - C++ and Paraview plugins: What is CMake, VTK and ITK – steps to install and compile. - Visualization – ITK-SNAP, Paraview. **Assignment #2** given (due on Monday 22 Sept.): - Basic software installation, code compilation and setup of software development environment (+ Ubuntu 12.04 virtual machines).

		- Visualization of imaging data from multiple modalities in 2D (ImageJ), 3D and 4D i.e. 3D + time in Paraview. - SimpleITK installation and iPython Notebook assignment. Reading assignment from Snyder Ch. 1-2.
18	Thur.	Begin class with a short **QUIZ #1** on Snyder Ch. 1-2. Math background – - Linear algebra & transformations, vector spaces, Fourier transformation, finite difference numerical discretization of partial differential equations, linear operators & convolution. - Vector products and operations, divergence, gradience, Laplacian. - Eigen values and eigen vectors. - Programming background – Review of basic script creation in Matlab and Python.
23	Tue.	Assignment #2 due for grading. Linear Systems Modeling of Biomedical Imaging Devices. - Linear model of Optical system and Optical system analysis. - Elements of Signal Processing, Nyquist Sampling theorem. The Point Spread Functions and Raleigh resolution limit. - Photon detection and noise. Noise models and linear inverse problems (primarily relating to image de-noising). Reading assignment from Snyder Ch. 4 (skip hexagonal coordinates on pp 57-59 & 71-73).
25	Thur.	Begin class with a short **QUIZ #2** on Snyder Ch. 4 Image formation and corruption. - General model of general biomedical imaging system. - *Resolution vs. Dynamic range*: Image bit depth and data loss. Image Characterization: - Brightness & Contrast: Windowing and leveling in radiology. - Image Histograms (examples in ImageJ). - Vector and scalar images. Example from Optical Flow and Computational Fluid Dynamics (demo in Tecplot). **Assignment #3** given (due on Monday 29 Sept.): - Problem solving: Math basics, vector algebra, orthogonalization, eigen vectors, linear transformations and function fitting. - Exploring images in k-space and Radon transforms, using Matlab. - Experimenting with basic image-processing operations in SimpleITK + Python code for understanding Dynamic Range.
30	Tue.	Assignment #3 due for grading. Mathematical Transforms in Tomographic Imaging: - CT: Filtered Back-Projection & Inverse Radon Transform. - MRI: k-space and Fourier Transform. FFT-shifting. - Understanding k-space: Image-blurring, edges and smoothing from the k-space perspective. Reading assignment on Linear Processing from Snyder 5.1-5.6,5.8-5A (through page 101, but skip 5.7).

October		
2	Thur.	**QUIZ #3** on Snyder Ch. 5. Spatial Image Filters: Image gradients, Hessian, edges and edge-detection. - Gaussian filtering - Feature detection: point feature detection o Pixel-level and subpixel-level particle feature - Feature detection: line/curve detection, Steger Algorithm. **Assignment #4** given (due on Monday 13 Oct.): - *Programming*: Pixel-level and subpixel-level particle feature detection in Matlab on a sample dataset. Reading assignment on Segmentation from Snyder ch. 8 (skip 8.3.2 on pp. 189-196 & 8A.1.1 on pp. 208-209)
7	Tue.	Segmentation (I). - Thresholding for segmentation. - Otsu threshold level selection. - Connected threshold filters and relevant operations in SimpleITK. Morphological Image Processing and relevant SimpleITK filters. - Dilation, Erosion, Opening, Closing o Relevant image-processing pipelines and examples. - Watershed Segmentation Reading assignment on level set segmentations &parametric transforms (Snyder 8.5.2 & Snyder 11.1-11.6). *Insight into Images* Ch. 8]
9	Thur.	**QUIZ #6** on Snyder ch. 8 and 11, as well as *Insight into Images*, Ch. 8. Segmentation (II). - Geometric and Parametric deformable models for segmentation. - Level Set Methods in 2D and 3D (Marching Cubes algorithm). - Active Contours / Snakes algorithm. - Energy Minimization
14	Tue.	Segmentation (III). - Performance Evaluation of Image Segmentation - Volumetric overlap, surface comparison error, Dice & Jaccard Indices, etc. - T-statistic and p-values to compare meshes. - Least Squares comparison, Normalized Correlation to compare images.
16	Thur.	Review of ITK and SimpleITK functions for segmentation & registration. - How to implement a detailed image-processing pipeline in SimpleITK, relevant to examples learned in our previous classes. - Description of C++ and Python starter code and how to use it. - Mat-ITK, with additional focus on the basic mathematical nature of segmentation operations relevant to region growing **Assignment #5** given (due on Monday 27 Oct.): - Segmentation and Image preprocessing using SimpleITK - Registration using Matlab toolboxes. Reading assignment on Registration in Depth from *Insight into Images* ch 10.

21	Tue.	**QUIZ #7** on *Insight into Images* Ch. 10. Registration Theory (I) - What is image registration – generalized workflow and overview of specific algorithms. - Intensity based, surface based and landmark based segmentation. - Registration theory: Salient linear transformation matrices – rotation, translation, scaling, projection. - Complex numbers and Quaternion representations of transformations. **Final Project discussion…** Discussion of prior project topics (i.e. from previous years in CMU) as well as data repositories of medical imaging or biological imaging data which can be employed for project work. Reading assignment on Deformable registration (*Insight into Images* Ch. 11)
23	Thur.	**QUIZ #8** on *Insight into Images* Ch. 11. Registration (II) - Deformable / Non-Rigid Registration (NRR) registration using Landmarks and Thin-Plate Spline bases. - Metrics of image-registration. - Intro to Mutual Information. **Assignment #5** given (due on Wednesday 29 Oct.): - Manual registration with Landmarks, using a Thin-Plate Splines basis. Reading assignment on Mutual Information from Viola & Wells 1996 .
28	Tue.	**QUIZ #9** on *Mutual Information* for registration. Registration (III): - Detailed overview of registration based on Mutual Information (Viola and Wells) - Joint Histograms and discussion of code for implementation of Mutual Information metrics.
30	Thur.	Assignment #5 due. Registration (IV): Physics based Registration Regularization. - Physics-based Regularization / Constraints for NRR. - Lagrangian and Eulerian operators for NRR - Optical Flow - Demons Algorithm Reading assignment on Cootes and Taylor *Active Shape Models* (ASM) (Cootes CVIU 1995)
November		
4	Tue.	**QUIZ #10** on *Active Shape Models* (Cootes & Taylor, 1995). Active Shape models: - Detailed overview of Cootes and Taylor ASM (Cootes CVIU 1995) - Principal Component Analysis. - Procrustes Analysis or shape alignment - Examples of shape models in the literature (eg: INRIA ExoShape).

6	Thur.	Active Appearance Models (AAM): - Detailed overview of Cootes and Taylor AAM (Cootes 1998) - Eigen faces. - Combined Shape & Appearance Models with biomedical examples. Reading assignment on Laplace Eigenvector decomposition and Spherical Harmonics (M. Chung, Wisconsin) + Synder Ch. 9 – Section 9.10, Surface harmonic representations. Reading on papers relating to biomedical applications of shape descriptors in the brain imaging (Herve Lombaert papers) and cardiac imaging space (Menon 2013-14: JCMR, SPIE, ICVTS, JCEC).
11	Tue.	*Statistical Shape Descriptors*: Advanced Shape Analysis, Shape Comparisons, and Segmentation Validation (includes Laplace Spectral Matching, Laplace Beltrami Operator, Spherical Harmonics, Medial Axis shape descriptors etc.) - Demo in Paraview on Laplace Spectral decomposition for shape-matching - Solving the correspondence problem to compare shapes. o Distance as a proxy for shape-comparison of co-registered shapes. - Other shape descriptors: o Elliptic Fourier Descriptors o Medial Axis Descriptors o Chain Code
13	Thur.	Biomarker Extraction, Data Mining and Classification: - k-means clustering - Naïve Bayes - Gaussian Mixture Models - Rule Learning - Graphical Models and Markov Modeling
18	Tue.	**Guest Lecture** on Signal Processing of Speech – similarities with image processing (Ming Li – To be Confirmed).
20	Thur.	Back-up Lecture slot – Lectures after 8 Oct may spill over owing to the length of Quiz #6. **Instructor away on conference: ASME IMECE 2014, Montreal, Canada**. + **Guest lecture** by Priti G. Albal, PhD student with The MeDCaVE. on application of image processing at the confluence of physics and computing for analysis of cardiovascular flow and medical device design. -
25	Tue.	FINAL LECTURE – Special Topics and Active Projects with The MeDCaVE. - After Segmentation: Mesh generation and pre-processing for computational simulation of mechanics & flow. - Open-source and reproducible projects of special note: o Eulerian Video Amplification o Diffeomorphic Spectral Matching o Graph-Based Visual Saliency and Eye Fixation on Images . - Gesture and eye-tracking based visualization enhancement technologies (LeapMotion, PrimeSense, Kinect, Tobii, etc.) - Building filters for Paraview. - Active projects in The MeDCaVE – current openings for student involvement.
27	Thur.	FINAL PROJECT PRESENTATIONS (4.5 - 5.5 min each) for the first hour, followed by Project Discussion Open-house…

December		
2	Tue.	Continuation of FINAL PROJECT PRESENTATIONS (4.5 - 5.5 min each)
5	Thur.	
8	Tue.	-
11	Thur.	-

Education Objectives (Relationship of Course to Program Outcomes)

(a) An ability to apply knowledge of mathematics, science, and engineering:
Theoretical lectures and tutorials are combined with practical exercises in programming and mathematical derivation / problem solving) to prepare students for a large-scale science/engineering final project relevant to image-processing as it relates to either medical imaging or biological imaging.

(b) An ability to design and conduct experiments, as well as to analyze and interpret data:
Class assignments and project work will require students to setup an image-processing software development environment and within this environment design, build, and run image-processing experiments in software to empirically or numerically optimize (through algorithm parameter tuning) their image-processing pipeline architectures to processing real medical or biological image data in the interest of addressing real-world image-processing problems for clinicians or biologists.

(c) An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability:
The final projects will require students to build a working software code that addresses a real clinical need, either by development of new computational tools at an algorithmic level or by appropriately researching and piecing together image-processing filters and mathematical operations available in open-source libraries or toolboxes in a sensible fashion. Through interaction with the instructor during class lectures as well as hands on work with real medical image data, students will be exposed to the challenges and constraints of biomedical image analysis in terms of computational burden / speed, usefulness and usability by a imaging practitioner (eg: Radiologist of Biologist).
Also see paragraph under section (f), below.

(d) An ability to function on multi-disciplinary teams:
This course integrates image-processing concepts with their real-world applications in the fields of mechanical and biomedical engineering, including computational simulation of mechanics or flow for improved medical diagnosis and treatment and image-guided surgery. These applications are inherently multi-disciplinary and homework assignments as well as the final project will require application of engineering approaches to biomedical problems in order to derive clinically meaningful end-points in terms of image quantification or classification or image-guidance for surgery.

(e) An ability to identify, formulate, and solve engineering problems:

As a project-based course with several assignments and quizzes along the way, students will constantly be solving engineering problems by hand (i.e. pencil and paper) or in terms of code (i.e. programming). For the final projects further, students will both identify relevant biomedical problems as well as formulate and then proceed to implement (at least partially) the engineering approach to address the identified biomedical problem.

(f) An understanding of professional and ethical responsibility:
Students will be working with de-identified medical imaging data in the DICOM format while being made aware of the issues of patient data privacy (HIPAA regulations) as well as the ethical concerns on patient safety and regulatory approvals (i.e. FDA clearances) as it relates to image-acquisition, data-handling and new medical image processing pipelines.

(g) An ability to communicate effectively:
Ongoing participation of students during the classroom discussions as well as the final projects will require both articulation of complex mathematical and conceptual information and individual student presentations. The latter will have presentation format equivalent to an oral conference presentation. Although students will be graded primarily on technical content, they will also be graded on the clarity, effectiveness and length of their presentations.

(h) The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context:
See paragraph on section (c), above.

(i) A recognition of the need for, and an ability to engage in life-long learning:
Biomedical imaging and image analysis is a driver for many recent developments in the medical and biological communities, ranging from medical diagnostics to design of new therapies, discovering molecular structures, cellular mechanisms and real-time surgical guidance. Students are shown from the beginning of the course that building useful systems requires awareness of the cutting edge and that a working knowledge of tools or techniques employed in contemporary workflows during clinical practice is required in order to define today’s limitations and engineer tomorrow’s novel technology solutions. These ideals are aligned with the goals of recognizing the importance of life-long learning as it relates to biomedical imaging and image-analysis software technologies.

(j) a knowledge of contemporary issues:
The course work and syllabus is built upon academic literature and commercial applications of medical imaging and image analysis will together form the cutting edge of biomedical imaging technology today. Students will require to consult with the latest scientific literature as part of their regular reading assignments as well as in order to address the project requirement in this course i.e. in regard to both project topic selection and implementation. The textbooks selected for this course as well as the lecture notes (i.e. slides) provide extensive references to active research groups and their work in the current literature.

(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice:

As a project based course, students are taught and required to make use of a wide variety of programs, open-source code and software libraries in addition to basic mathematical skills and programming in order to solve biomedical image analysis problems. Therefore, the course exposes students to a wide range of techniques, skills, and modern engineering tools necessary for engineering practice in the biomedical imaging industry.

Academic Integrity Policy (http://www.ece.cmu.edu/student/integrity.html):

The Department of Electrical and Computer Engineering adheres to the academic integrity policies set forth by Carnegie Mellon University and by the College of Engineering. ECE students should review fully and carefully Carnegie Mellon University's policies regarding Cheating and Plagiarism; Undergraduate Academic Discipline; and Graduate Academic Discipline. ECE graduate student should further review the Penalties for Graduate Student Academic Integrity Violations in CIT outlined in the CIT Policy on Graduate Student Academic Integrity Violations. In addition to the above university and college-level policies, it is ECE's policy that an ECE graduate student may not drop a course in which a disciplinary action is assessed or pending without the course instructor's explicit approval. Further, an ECE course instructor may set his/her own course-specific academic integrity policies that do not conflict with university and college-level policies; course-specific policies should be made available to the students in writing in the first week of class.

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Cheating and Plagiarism (http://www.cmu.edu/policies/documents/Cheating.html) states the following,

> Students at Carnegie Mellon are engaged in preparation for professional activity of the highest standards. Each profession constrains its members with both ethical responsibilities and disciplinary limits. To assure the validity of the learning experience a university establishes clear standards for student work.
>
> In any presentation, creative, artistic, or research, it is the ethical responsibility of each student to identify the conceptual sources of the work submitted. Failure to do so is dishonest and is the basis for a charge of cheating or plagiarism, which is subject to disciplinary action.
>
> *Cheating* includes but is not necessarily limited to:
> 1. Plagiarism, explained below.
> 2. Submission of work that is not the student's own for papers, assignments or exams.
> 3. Submission or use of falsified data.
> 4. Theft of or unauthorized access to an exam.
> 5. Use of an alternate, stand-in or proxy during an examination.
> 6. Use of unauthorized material including textbooks, notes or computer programs in the preparation of an assignment or during an examination.
> 7. Supplying or communicating in any way unauthorized information to another student for the preparation of an assignment or during an examination.
> 8. Collaboration in the preparation of an assignment. Unless specifically permitted or required by the instructor, collaboration will usually be viewed by the university as cheating. Each student, therefore, is responsible for understanding the policies of the department offering any

course as they refer to the amount of help and collaboration permitted in preparation of assignments.

9. Submission of the same work for credit in two courses without obtaining the permission of the instructors beforehand.

Plagiarism includes, but is not limited to, failure to indicate the source with quotation marks or footnotes where appropriate if any of the following are reproduced in the work submitted by a student:

1. A phrase, written or musical.
2. A graphic element.
3. A proof.
4. Specific language.
5. An idea derived from the work, published or unpublished, of another person.

This policy applies, in all respects, to (J1-791).