Syllabus for the course «Digital Signal Processing»

(4 ECTS)

Authors: Alexey Ossadtchi, PhD, Director of Centre for Bioelectric Interfaces of Institute of Cognitive Neuroscience, professor of Faculty of Computer Science, School of Data Analysis and Artificial Intelligence of the National Research University Higher School of Economics

Meeting Minute: MP Academic Council, Protocol №2.6-06/7 29/08/2019.

1. **Course Description**
   a. «Digital Signal Processing»
   b. **Pre-requisites**

      The course is based on the basic knowledge of mathematical analysis and linear algebra concepts obtained by the students during their first semester at the program. The course is oriented to students with humanitarian background and will maximize the use of plots and pictures rather than equations and formal proofs to introduce the main concepts.

      The following knowledge and competence are needed to study the discipline:

      A good command of the English language.

      A basic knowledge in mathematics: fundamentals of calculus, fundamentals of linear algebra
   c. **elective**
   d. **Abstract**

      In modern science system's based approach is frequently exercised as it allows to formalize the problems encountered in the real world by representing them in the well studied framework that provides for efficient analysis and solution. In order to get a full grip of his powerful machinery researchers need to understand the fundamentals principles of the theory. The existing classes are either too specialized and mathematically detailed or too much of a cook-book nature. The goal of this class is to provide master students of non-mathematical background with a unifying view on the theory behind the system-oriented approach. The main goal is to develop the intuition behind the complex concepts. We will attempt to do it by showing the similarity of discrete and continuous treatments of the system's theory and interpret the results using the natural concepts of linear algebra. The second part of the class is primarily dedicated to the fundamentals of estimation theory. We start from the basic concepts and estimation of model parameters in the white and colored noise cases. We will then introduce the

Maximum Likelihood and Bayesian approaches to the problem of parameter estimation. We will illustrate the Bayesian methodology via examples of solving the inverse problem in neuroimaging and spectroscopy. We will use the Bayesian concept to develop Kalman filters - advanced model-based estimators taking into account the dynamical properties of the signals.

2. Learning Objectives

Learning objectives of the "Digital signal processing" class are to provide students with the unifying view on the theory behind system oriented approach in the modern science and to demonstrate the equivalence of "continuous" and "discrete" approaches.

The following grand topics will be covered and supported by an extensive weekly homework assignments and practical sessions.

1. Signals
2. Transforms and decompositions
3. Statistical description of signals in original and transformed spaces
4. Linear time invariant systems
5. Digital filters

3. Learning Outcomes

After completing the study of the "Digital signal processing" the student should:

- Know the definition of signal, basic model signal types, understand the difference between the continuous and discrete signals, be able to formally write an expression of an arbitrary signal, be able to show the link between the continuous and discrete treatments, be able to explain the role linear algebra plays in signal processing.

- Understand the notion of a transform, be able to interpret a transform in the linear algebra framework, be familiar with basic transforms used (Fourier transform, Wavelet transform), be able to formulate one's own transform and write expressions for the coefficients and synthesis equation, be able to connect statistical properties of signals on both sides of the transform operation.

- Understand the notion of system, understand why LTI systems is an important class of systems, know what convolution operation is, be able to calculate the output of an arbitrary LTI system, be able to relate statistical properties of the output signal to those of the input

- Understand methods for statistical description of random processes, relation between times and frequency domain representation of second order statistical descriptors of random processes

- Be able to perform z-domain analysis of digital filters, predict their frequency response, assess their characteristics e.g. group-delay, pass-band ripples, stop-band attenuation etc.

After completing the study of the discipline «Digital signal processing» the student should develop the following skills:

1. The student will be able to reflect developed mathematical methods to psychological fields and problems.
2. The student will obtain necessary basic knowledge in signals, harmonic analysis and systems theory
3. The student will be able to describe psychological problems in terms of computational mathematics.
4. The student will be able to identify systems theory aspects in psychological and neurobiological research tasks and suggest a method to tackle the problem and rank several available techniques in the order of applicability in the current situation.

4. Course Plan

№	Topic
1.	Signals 1. Deterministic Signals (discrete, continuous) 2. Signals as vectors

	3. Hilbert space, infinite dim Eucledian space, notion of distance 4. Demonstrated equivalence of discrete and continuous forms of treatment
2.	Transforms and decompositions 1. General idea of a transform 2. A transform as a change of basis 3. Calculating transform coefficients or why do we need an orthogonal basis? 4. Fourier transform i. Periodic signals ii. Aperiodic signals iii. Discrete Fourier transform 5. State-space representation and discrete transforms as a matrix-vector multiplication 6. Time-frequency representation of signals 7. Short-time Fourier transform 8. Wavelet transform
3.	Random signals, random processes 1. Mean, std, autocorrelation function, distribution function 2. Properties of random signals (stationarity, ergodicity) 3. Scalar and vector random processes
4.	Statistical description of signals in the original and transformed spaces 1. Second order statistical description of random signals revisited 2. Periodogram, Power spectral density(PSD)

	3. Wiener-Hinchin theorem 4. Methods to compute PSD
5.	Linear systems 1. Input-output relation, a system as an operator 2. Calculation of an output of a system for an arbitrary input, pulse response 3. Linear time invariant (LTI) systems 4. Transient processes 5. Passing random process through an LTI system 6. Time domain 7. Frequency domain, Transfer function or why a linear system cannot "bring in new frequencies" 8. Z- transform as a method for analysis of discrete-time LTIs 9. Digital Temporal filters as most frequently used LTIs 10. FIR, IIR filters, 11. Stability, implementation details
6.	Practical examples and Summary

5. Reading List

a. Required

1. Probability and random processes: with applications to signal processing and communications / S. L. Miller, D. Childers. – Amsterdam [etc.]: Elsevier: Academic Press, 2004. – 536 с. – На англ. яз. - ISBN 0-12-172651-7.
2. Statistical signal processing: frequency estimation / D. Kundu, S. Nandi. – New delhi [etc.]: Springer, 2012. – 132 с. – (Springer briefs in statistics) . – На англ. яз. - ISBN 978-81-322-0627-9.

b. Optional

1. A course in time series analysis / Ed. by D. Pena, G. C. Tiao, R. S. Tsay. – New York: John Wiley & Sons, 2001. – 460 с. – (Wiley series in probability and statistics) . – На англ. яз. - ISBN 0-471-36164-X.
2. The signal and the noise: why so many predictions fail - but some don't / N. Silver. – New York: The Penguin Press, 2012. – 534 с. – На англ. яз. - ISBN 978-1-594-20411-1.

6. Grading System

The assessment consists of classwork and homework, assigned after each lecture. Students have to demonstrate their knowledge in each lecture topic concerning both theoretical facts, and practical tasks' solving. All tasks are connected through the discipline and have increasing complexity.

Intermediate assessment is in the form of two midterm exams. Students have to demonstrate knowledge of theory facts, but the most of tasks would evaluate their ability to solve practical examples, present straight operation, and recognition skills to solve them.

Final assessment is the final exam. Students have to demonstrate knowledge of theory facts, but the most of tasks would evaluate their ability to solve practical examples, present straight operation, and recognition skills to solve them. While comprehensive will primarily focus on the second part of the class (Estimation theory)

The grade formula:

Each exam (midterm and the final) will consist of 5 problems, giving two points each.

Final course mark *is obtained from the following formula*:

Ofinal = 0,5*O hw+0,3*Omte+ 0.2*Ofe

The grades are rounded in favor of examiner/lecturer with respect to regularity of class and home works. All grades, having a fractional part greater than 0.5, are rounded up.

Table of Grade Correspondence

Ten-point Grading	Scale Five-point Grading Scale	
1 - very bad 2 – bad 3 – no pass	Unsatisfactory – 2	FAIL
4 – pass 5 – highly pass	Satisfactory – 3	PASS
6 – good 7 – very good	Good – 4	

8 – almost excellent 9 – excellent 10 – perfect	Excellent – 5	

The final grade, which is the resultant grade for the course, goes to the certificate of Master's degree.

7. Guidelines for Knowledge Assessment

Type of grading	Type of work	1st year	Characteristics
		3	
Continuous	Home work assignments	*	Take home assignments.
Intermediate	Midterm Exam	*	Written exam with 5 problems to solve.
Final	Final Exam	*	Written exam with 5 problems to solve

Continuous assessment:

Homework assignments will be given after each lecture and will include written and programming exercises. Assignments are designed to enable grading along correct/incorrect answers to specific questions in each exercise. Total number of questions will be 10. Each correct answer adds one point. The grade is calculated as the percentage of correct answers to the total number of questions and converted to a ten-point grading scale.

Ten-point grade	Criteria
0 – not accepted	Less 5%, or the homework was not submitted
1 – very bad	Not less than 5, but less than 15%
2 – bad	Not less than 15, but less than 25%
3 – no pass	Not less than 25, but less than 35%

4 – pass	Not less than 35, but less than 45%
5 – highly pass	Not less than 45, but less than 55%
6 – good	Not less than 55, but less than 65%
7 – very good	Not less than 65, but less than 75%
8 – almost excellent	Not less than 75, but less than 85%
9 – excellent	Not less than 85, but less than 95%
10 – perfect	Not less than 95% and greater

Final exam assessment:

Final assessment is the written final exam. There will be 5 problems designed to enable grading along correct/incorrect answers to specific questions in each exercise. Each correct answer adds two points. The grade is calculated as the percentage of correct answers to the total number of questions and converted to a ten-point grading scale.

Final exam topics:

1. Deterministic Signals(discrete, continuous)
2. Random signals, random processes
3. Mean, std, autocorrelation function, distribution function
4. Properties of random signals (stationarity, ergodicity)
5. Scalar and vector random processes
6. Signals as vectors, Hilbert space, infinite dim Eucledian space, notion of distance
7. Demonstrate equivalence of discrete and continuous forms of treatment
8. General idea of a transform
9. A transform as a change of basis
10. Calculating transform coefficients or why do we need an orthogonal basis?
11. Fourier transform, periodic signals
12. Fourier transform, Aperiodic signals
13. Discrete Fourier transform

14. State-space representation and discrete transforms as a matrix-vector multiplication
15. Time-frequency representation of signals, Short-time Fourier transform
16. Time-frequency representation of signals, Wavelet transform
17. Second order statistical description of random signals(Periodogram, Power spectral density(PSD))
18. Wiener-Hinchin theorem, methods to compute PSD
19. Autoregressive model
20. Autoregressive moving average model
21. Parameter estimation: problem statement
22. Input-output relation, a system as an operator
23. Calculation of an output of a system for an arbitrary input, pulse response, Linear time invariant (LTI) systems
24. Transient processes
25. Passing random process through an LTI system (time domain analysis)
26. Passing random process through an LTI system (frequency domain, transfer function)
27. Z- transform as a method for analysis of discrete-time LTIs
28. Digital Temporal filters as most frequently used LTIs
29. FIR, IIR filters, stability, implementation details

8. Methods of Instruction

The following educational technologies are used in the study process:

· Lectures involving continuous use of multimedia presentations and on-line simulations

· Seminars involving team oral discussions, solving of exercises and problems, programming simulations and examples

· Homework assignments

· Self-study of lectures

· Self-study of recommended literature

Course lecturer is advised to use interactive learning methods, which allow participation of the students, such as discussions. It is also expected that multimedia presentations and video materials will be intensively used for the study process. Students are required to study the lecture materials and the required reading. Students are invited to ask questions and actively participate in group discussions. There will be special office hours for students, which would like to get more precise understanding of each topic. Teaching assistant will also help you. All tutors are ready to answer your questions online by official e-mails that you can find in the “contacts” section**.**

9. Special Equipment and Software Support (if required)

The course requires a computer or laptop, projector, and acoustic systems for multimedia presentations and video.