Department of Aeronautics and Astronautics
School of Engineering
Massachusetts Institute of Technology

Graduate Program (S.M., Ph.D., and Sc.D.)

Field: Engineering Systems
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1. Introduction and Purpose

The graduate program in the Department of Aeronautics and Astronautics at M.I.T. provides educational opportunities in a wide variety of aerospace-related topics through academic subjects and research. The purpose of this document is to provide incoming masters and doctoral level students guidance in planning the subjects they will take during their graduate program.

The focus of this document is the field of *Engineering Systems*. The suggestions outlined here are to be understood as guidance and not as a mandatory, rigid framework. The final decision as to which subjects are taken and in what sequence is to be decided between each student and their academic advisor and/or doctoral committee. In addition to these recommendations, the official S.M. and doctoral degree completion requirements must be taken into account during the design of a graduate program.[1]

2. Motivation for Studying Engineering Systems

Aerospace systems today can be viewed as complex sociotechnical systems. Examples of such systems are the new generation of federated satellite constellations or satellites and high altitude drones working together as a federated system-of-systems. Many of the significant problems in producing effective aerospace systems today lie beyond the traditional aerospace disciplines (such as structures, aerodynamics and controls) and encompass new ways to create and operate these systems to achieve the overall goals throughout the entire system lifecycle, from early design activities to deployment and during the operational life time. Some of the most significant aerospace engineering challenges lie in creating new frameworks and approaches to decision-making at the larger, integrated system level and not just at the component level or at the individual vehicle level.

Systems today may have millions of parts, all of which must work together to achieve the overall system goals while satisfying constraints (such as safety and security) on how those goals can be achieved. In such systems, early design decisions have a *disproportionate* impact on

- System performance
- Lifecycle cost
- Lifecycle properties (e.g. the flexibility of a system to perform other missions or to perform their original mission as the system and the environment evolve and change around it)
- Stakeholder value delivered

[1] Refer to the S.M., Ph.D. and Sc.D. degree requirements in Aeronautics and Astronautics section of the MIT Bulletin, or to http://web.mit.edu/aeroastro/academics/grad/index.html

There is a need for *formal methods* and tools to assist in making these decisions. Examples of formal methods in Engineering Systems are architectural decision graphs, safety control structures, agent based modeling or multi-objective systems optimization to find the Pareto front of non-dominated alternatives.

In addition, seeking more performance and resilience at lower cost is leading to increasing levels of complexity due to:

- Infusion of new technologies
- Shifting from monolithic to more distributed systems
- Trading of multiple competing objectives (performance, cost, energy) against each other

To make progress, we need to better understand the impact of complexity on engineering. The overall goal of Engineering Systems is to determine how to create more effective sociotechnical systems. How to design and operate such systems is an important current topic that will only grow in the future.

3. What is Engineering Systems?

Engineering Systems students study the underlying principles and methods for designing complex socio-technical systems that involve a mix of architecture, technologies, organizations, policy issues, and complex networked operations. The focus is on aerospace and other complex systems critical to society. A unique emphasis is on designing system safety and cybersecurity into systems from the beginning of development. Another topic is how to infuse new technologies into complex systems over time. While the other fields in the department study how to create new types of propulsion, materials, human-computer interfaces, etc., Engineering Systems studies how to integrate these technologies into effective, useful, safe, and secure systems and how to operate these systems to ensure that the goals and constraints are maintained during their lifetime. We study these topics in collaboration with stakeholders from government, industry, and non-profit organizations.

Examples of Engineering Systems are shown in Figure 1.

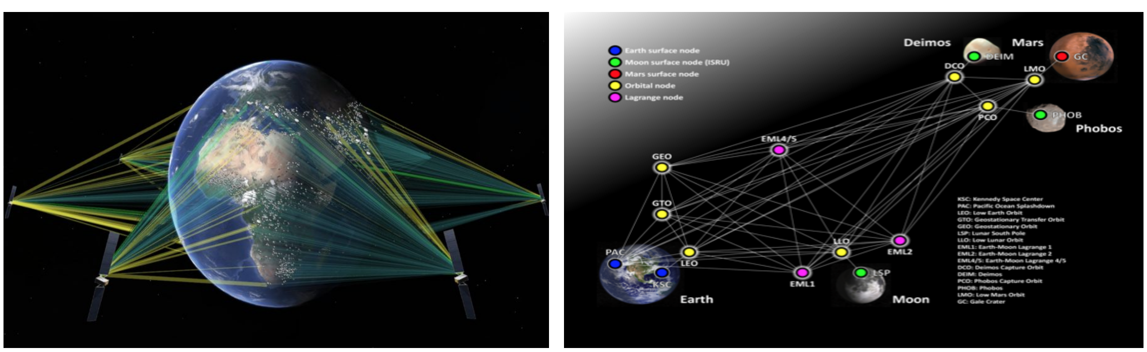

Fig. 1 (left) Telecommunications Satellite Constellation[2], (right) Interplanetary Supply Chain[3]

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[2] Guerster, Markus, Juan Jose Garau Luis, Edward Crawley, and Bruce Cameron. "Problem representation of dynamic resource allocation for flexible high throughput satellites." In *2019 IEEE Aerospace Conference*, pp. 1-8. IEEE, 2019

[3] Ishimatsu, Takuto, Olivier L. de Weck, Jeffrey A. Hoffman, Yoshiaki Ohkami, and Robert Shishko. "Generalized multicommodity network flow model for the earth–moon–mars logistics system." *Journal of Spacecraft and Rockets* 53, no. 1, pp. 25-38, 2016

There are currently three main topics being pursued in the field of Engineering Systems:

- **System Architecture**: System architecture is the study of the early-stage technical decisions that will determine the majority of the system's performance. By identifying the most important initial technical decisions and exhaustively enumerating their options, the best potential designs are identified prior to the detailed design activities. The approach stands in contrast to a traditional trade-study perspective, where two to four points designs are compared, without reference to the intervening options or to a fully explored tradespace. The emerging field of System Architecture aims to understand what patterns emerge across disparate domains, to gain an understanding of the making of good architecture. System architecture models look broadly across possible technologies, subsystems, and use contexts. Although each model employs problem-specific parameters, together they advance the state of the art by developing unique and generalizable approaches to structuring complex systems architecting problems that can be applied across disciplines.

- **Strategic Engineering:** Strategic engineering involves the study of long-lived systems on Earth and in space. This includes the design and operation of critical infrastructures such as industrial manufacturing, transportation, earth observation, defense, water, energy and food supply systems as well as the challenges of sustained human and robotic exploration and settlement of outer space. Research involves developing validated models and simulations to support strategic decisions under uncertainty, including selection of technologies and system evolutionary pathways. Methodologies in strategic engineering include multidisciplinary design optimization, Monte Carlo simulation, multicommodity network flows and other techniques based on discretizing systems both in time and space

- **System Safety and Security:** The goal of safety and security engineering is to create new tools and processes to reduce losses, both in terms of human life and property, but also losses related to mission, scientific, and business goals. Engineering safer systems requires multi-disciplinary and collaborative research based on sound system engineering principles, that is, it requires a holistic systems approach. A focus is on modeling and analysis tools based on systems theory to identify the constraints on how a system can achieve its goals and to ensure the constraints are enforced while the goals are also achieved. The analysis includes hardware, software, humans, and organizational/management decision making. Some current and recent research topics include creating concepts and requirements for defense systems, human-automation interaction, aircraft type certification, safety in airline operations, conceptual architectures for safety and cybersecurity, and safety of systems incorporating AI.

Books published by MIT Engineering Systems faculty in recent years that form the basis of the field of Engineering Systems are shown in Fig. 2.

Fig. 2 Books published by MIT faculty on System Architecture[4], Engineering Systems[5], and Safety[6]

4. Educational Goals in Engineering Systems

The educational goal of the MIT graduate program in Engineering Systems is to provide students with a foundational understanding and a working knowledge of the technical issues surrounding the design, operation, and management of complex systems made up of a variety of hardware, software, human, and social components.

Successful graduates of the program will have:

- A fundamental understanding of system engineering in terms of the technologies, principles, methods and tools required to conceive, design, implement, and operate complex sociotechnical systems.
- The ability to take a holistic systems approach to problems that optimizes emergent properties of systems as a whole and can integrate independent technologies and system components to identify and achieve system goals and constraints.
- The ability to model and analyze complex, socio-technical systems with real world complexity and to influence their design and operation in the real world
- Generated research contributions to the current engineering systems body of knowledge.

To achieve these goals, each student should develop an educational plan with their academic advisor following the guidelines outlined below.

[4] Cameron, Bruce, Edward Crawley, and Daniel Selva. *Systems Architecture. Strategy and product development for complex systems*. Pearson Education, 2016.

[5] de Weck, Olivier L., Daniel Roos, and Christopher L. Magee. *Engineering systems: Meeting human needs in a complex technological world*. MIT Press, 2011.

[6] Leveson, Nancy G. *Engineering a safer world: Systems thinking applied to safety*. The MIT Press, 2016.

5. Educational Plan in Engineering Systems

Students interested in Engineering Systems typically enter the program with a basic background in aerospace engineering, or another field of engineering. While exceptions may be made, most students will complete the following core coursework:

Core Courses: These three core classes are required although students can make substitutions with the approval of their advisor:

16.842 *Fundamentals of Systems Engineering*
16.863 *System Safety*
16.888 *Multidisciplinary Design*

In addition, students in Engineering Systems should at some time take a class on discrete mathematics, that covers topics such as network and graph theory, Boolean algebra or discrete time control systems. Meeting this requirement and identifying any gaps in knowledge will be discussed between the student and their advisor and doctoral committee.

Engineering systems students will also have experience on a real project. That can be obtained through a variety of means, including project classes and industrial experience.

Elective Courses
16.355 - IDS.341 *Concepts in the Engineering of Software-Intensive Systems*
16.89 - IDS.339 *Space Systems Engineering*
16.887 - EM.427 *Technology Roadmapping and Development Technology*
16.895J *Engineering Apollo: The Moon Project as a Complex System*
16.422 *Human Supervisory Control of Automated Systems*
6.914 *Project Engineering*
16.851 *Satellite Engineering*

7. Faculty and Staff with Interests in Engineering Systems

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Please consult the MIT Aeronautics and Astronautics webpage for detailed faculty and staff interests: https://aeroastro.mit.edu/faculty-research/faculty-list