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

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

Field: Space 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 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 Space Systems

Thousands of manned and unmanned spacecraft have been launched into space since the launch of Sputnik on October 4, 1957. We have landed men on the moon, visited every planet in our solar system with robotic probes, have established global telecommunication and navigation systems in Low Earth Orbit (LEO) and Geostationary Orbit (GEO), have launched numerous scientific and military satellites that gather a wealth of data about Earth's climate, surface conditions and weather. Despite all these accomplishments many challenges remain:

Manned Space Exploration: A major driver in the coming two decades will be the return of human explorers to the Moon. It is becoming clear that a symbiosis of man-and-machine yields the best results in a challenging space environment. The optimal interactions between robots and humans during space operations need to be better understood. The responses of the human body to long-term weightlessness or sub one-g conditions and relative isolation need to be researched and influenced as an enabler for long-distance human exploratory missions such as to the planet Mars, the natural extension of the Moon exploration program. A detailed understanding of interplanetary logistics, involving the flow of crews, consumables and spares, among other supplies, needs to be developed to ensure safety, effectiveness and affordability of future operations.

[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

Space Science: The rising awareness of climate change on Earth demands new sensor systems that can measure atmospheric and surface properties in real-time with full global coverage. This might be accomplished with small distributed arrays of spacecraft (distributed satellite systems) rather than traditional, large and expensive single satellites.

The next generation of space observatories will tackle grand challenges such as the direct detection of Earth-like planets around neighboring stars, the investigation of the early universe after the Big Bang, the search for dark matter and ultra-precise star maps among other investigations. These observatories will need to operate at far away Lagrange points such as the Earth-Sun-L2. They will be light-weight, cryogenic (<50K) and capable of precise micro-arc second pointing accuracy over several weeks of observing time. These requirements all represent daunting engineering challenges and important research opportunities.

Commercial Space: Beyond technical feasibility, further improvements are needed to make communications satellite systems more economical and better integrated into the global communications network including terrestrial fixed and cellular systems.

Space entrepreneurship is energized after the X-Prize in 2004 and numerous larger and smaller companies are now developing systems and concepts for commercial services in the area of space tourism (e.g. sub-orbital flights, orbital space hotels) as well as logistics services in near-Earth space (e.g. resupply of the International Space Station).

Military Space Systems: The modern military concepts of long range all weather, highly mobile warfare are enabled by use of space assets. Several shifts are taking place, where the goals are to provide “information superiority” to the individual warfighter as well as provide real time, high bandwidth data connectivity between aircraft (manned and unmanned), spacecraft, ships and ground troops.

These challenges make it apparent that the success or failure of space systems depends not only on functionality and performance never before achieved by individual components but on the overall integration of the launch, space and ground segments with human operators, in the context of policy, market and technological uncertainty. This is the major challenge for space systems engineers.

Selected examples from MIT space systems research are shown in Figure 1.

Figure 1: left: KC-135 micro-gravity testing of SPHERES, middle: Electromagnetic Formation Flying (EMFF) Testbed, right: proposal for a modular human transportation system for Moon and Mars (Draper/MIT CE&R study 2004-2005).

3. What is Space Systems Engineering?

In order to be successful as a space systems engineer a good working knowledge of satellite subsystems and general spacecraft technologies is required. One of the main tasks of systems engineers in practice is to conduct trades among alternative architectures and negotiate requirements with various stakeholders, including the customer, program management and the various subsystem teams. Depth and advanced knowledge in at least one of the subsystem technologies (e.g. controls, structures, software and autonomy, payload engineering such as optics or radio frequency communications …) is paramount in order to establish acceptance, credibility and fluency in the common technical vocabulary of space systems.

A second key aspect is teamwork and the communication necessary to make teamwork functional. No space system has ever been built by a single individual! While simple aircraft can be designed, built and flown by a single person, this is not possible for satellites. The complexity of space systems and the requirements for launch, operations in the harsh environment of outer space, wireless communications around the globe make effective collaboration a key requirement. These two aspects, spacecraft engineering knowledge and development of a space system or mission as a team are at the core of our program in space systems.

One of the marks of excellence of MIT engineers is that they should both possess breadth and technical depth at the same time. The space systems faculty deems it important space systems engineering remains strongly rooted in the technical disciplines. A candidate can tailor a program that provides depth in a technical specialty such as controls, structures and dynamics, software and autonomy, communications, astrodynamics, propulsion and humans & automation among others while learning about most of the others. This approach to the curriculum design is described in the next section.

4. Educational Goals in Space Systems

The overall educational goal of our educational program in Space Systems Engineering is to provide students with a foundational understanding of the systems engineering principles, methods and tools required to transform fundamental technical, economic and societal requirements into an integrated space system solution. This integration encompasses hardware, software and humans, embedded in a clearly articulated value proposition and overall system architecture.

Successful graduates of the program will have achieved the following objectives:

- They will have gained a fundamental understanding of space systems engineering in terms of the technologies, principles, methods and tools required to conceive, design, implement and operate a space system.

- They will have exercised this knowledge for the design of a particular space mission in the context of a development team.

- They will have established credibility and depth in a discipline with either a technology focus (e.g. control, optics, structures…) or process focus (e.g. optimization, manufacturing, space policy, operations…).

- They will have gained experience in the field by having applied this knowledge in the context of a space related industrial enterprise or government organization.

- They will have generated research contributions to the current space systems engineering body of knowledge.

To achieve this goal, each student should develop an educational plan with their academic advisor and/or doctoral committee following the guidelines outlined below.

5. Educational Plan in Space Systems

The educational goals outlined above lead to a proposed recommended program of study for space systems, see Figure 2. The document proposes a program structure that will accommodate masters and doctoral candidates alike.

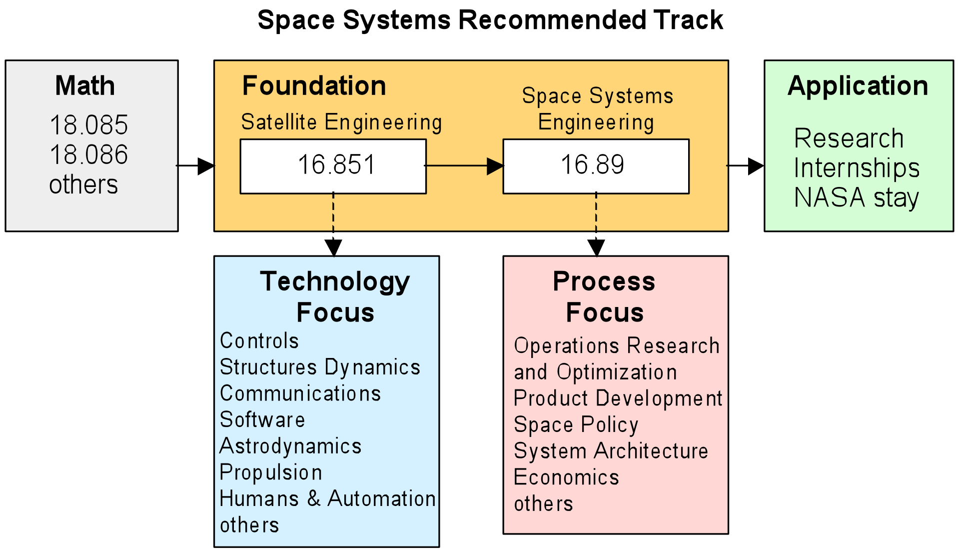

Figure 2: Recommended Space Systems Program of Study

The foundation courses provide a foundation of knowledge in the variety of sub-systems that comprise a space system, the methods for developing a mission concept, the dynamics of a team environment, and the space systems context within which a field of systems research lies. The two foundation courses include Satellite Engineering (16.851), and Space Systems Engineering (16.89). Generally 16.851 should be taken before taking 16.89, it can be considered an implicit prerequisite. Both 16.851 and 16.89 are considered the header courses of the space systems.

In addition to the foundation courses, students focusing on space systems should carefully select a set of follow-on courses from either a technology or process focus area. Which area and courses to select depends on the student's interest and research needs. A list of recommended follow-on courses in those areas is shown below.

Additionally all students have to meet the departmental mathematics requirement (see separate document available from the graduate student office) with two graduate level mathematics courses. The department keeps a list of mathematics courses that are acceptable for fulfillment of this requirement.

This structure should help a master's student assemble a coherent space systems oriented program, which leads to a S.M. in Aeronautics and Astronautics with emphasis on space systems. The degree requirement [MIT Catalogue] specifies 66 units, which corresponds to 6 graduate level 12-unit subjects or five 12-unit subjects and one 6-unit subject. Based on past experience most master's candidates significantly exceed this requirement.

Doctoral candidates in space systems will generally follow this structure, but naturally surpass the depth of knowledge and number of classes taken by master's students.

6. Courses related to Space Systems

The header courses are:

16.851	Satellite Engineering
16.89J	Space Systems Engineering

Suitable follow-on courses are in both the technology focus and process focus areas:

Technology Focus

Dynamics and Controls

16.31	Feedback Control Systems
6.245	Multivariable Control Systems (MCS)
16.322	Stochastic Estimation and Control
16.323	Principles of Optimal Control
16.335	Spacecraft Dynamics and Control
6.231	Dynamic Programming and Stochastic Control
2.151	Advanced System Dynamics and Control

Materials, Structures, Structural Dynamics

16.221	Advanced Structural Dynamics
16.223	Mechanics of Heterogeneous Materials
16.225	Computational Mechanics of Materials
16.230	Plates and Shells

Astrodynamics, Propulsion and Flows

16.100	Aerodynamics
16.120	Compressible Flow
16.346	Astrodynamics
16.512	Rocket Propulsion
16.522	Space Propulsion
16.55	Ionized Gases

Communications, Sensors and Software

16.343	Spacecraft and Aircraft Sensors and Instrumentation
16.36	Communication System Engineering (can be taken as G-level)
16.37J	Data-Communication Networks
6.442	Optical Communications and Networks
16.355J	Concepts in the Engineering of Software
16.863	System Safety
6.852	Distributed Algorithms
6.661	Receivers, Antennas and Signals
6.630	Electromagnetics
6.631	Optics and Photonics

Robotics

2.165	Robotics
16.412	Cognitive Robotics

Humans and Automation

16.423/HST.515J	Aerospace Biomedical and Life Support Engineering
16.422J	Human Supervisory Control of Automated Systems
16.431	Flight Simulation and Virtual Environments
16.453J	Human Factors Engineering

Other technology fields are possible as discussed with the advisor and/or committee.

Process Focus

Modeling and Simulation, Optimization

16.888	Multidisciplinary System Design Optimization
15.073	Logistical and Transportation Planning Methods
16.910J	Introduction to Numerical Simulation
6.251	Introduction to Mathematical Programming
15.083J	Integer Programming and Combinatorial Optimization
15.084J	Nonlinear Programming

Systems Engineering, Product Development, and Project Management:

ESD.33	Systems Engineering
ESD.36	System Project Management
2.739J	Product Design and Development
2.744	Product Design
16.810	Engineering Design and Rapid Prototyping (can be taken G level)
2.760	Multi-Scale System Design and Manufacturing
2.810	Manufacturing Processes and Systems
2.851J	System Optimization and Analysis for Manufacturing

Space Policy and Enterprise Architecting

16.891J/ESD.129J	Space Policy Seminar
16.852J	Integrating the Lean Enterprise
ESD.10	Introduction to Technology and Policy
ESD.103J	Science, Technology and Public Policy
ESD.163J	Managing Nuclear Technology
ESD.260J	Logistics Systems
16.855/ESD.38J	Enterprise Architecting

Recommended mathematics courses in space systems are:

18.085	Mathematical Models for Engineers I
15.064	Engineering Probability and Statistics
15.085	Fundamentals of Probability

7. Faculty and Staff with Interests in Space Systems

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Please consult the MIT Aero & Astro web-page for detailed faculty and staff interests:
http://web.mit.edu/aeroastro/faculty/faculty.html