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.

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.

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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](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.
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 speciality 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.
The foundation courses provide a foundation of knowledge in the variety of subsystems 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:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
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<tbody>
<tr>
<td>16.851</td>
<td>Satellite Engineering</td>
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<tr>
<td>16.89J</td>
<td>Space Systems Engineering</td>
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Suitable follow-on courses are in both the technology focus and process focus areas:

**Technology Focus**

**Dynamics and Controls**

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<tr>
<th>Course Code</th>
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<tbody>
<tr>
<td>16.31</td>
<td>Feedback Control Systems</td>
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<tr>
<td>6.245</td>
<td>Multivariable Control Systems (MCS)</td>
</tr>
<tr>
<td>16.322</td>
<td>Stochastic Estimation and Control</td>
</tr>
<tr>
<td>16.323</td>
<td>Principles of Optimal Control</td>
</tr>
<tr>
<td>16.335</td>
<td>Spacecraft Dynamics and Control</td>
</tr>
<tr>
<td>6.231</td>
<td>Dynamic Programming and Stochastic Control</td>
</tr>
<tr>
<td>2.151</td>
<td>Advanced System Dynamics and Control</td>
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**Materials, Structures, Structural Dynamics**

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<tr>
<th>Course Code</th>
<th>Course Title</th>
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<tbody>
<tr>
<td>16.221</td>
<td>Advanced Structural Dynamics</td>
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<td>16.223</td>
<td>Mechanics of Heterogeneous Materials</td>
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<td>16.225</td>
<td>Computational Mechanics of Materials</td>
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<td>16.230</td>
<td>Plates and Shells</td>
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**Astrodynamics, Propulsion and Flows**

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<tr>
<th>Course Code</th>
<th>Course Title</th>
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<tr>
<td>16.100</td>
<td>Aerodynamics</td>
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<tr>
<td>16.120</td>
<td>Compressible Flow</td>
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<tr>
<td>16.346</td>
<td>Astrodynamics</td>
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<tr>
<td>16.512</td>
<td>Rocket Propulsion</td>
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<td>16.522</td>
<td>Space Propulsion</td>
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<td>16.55</td>
<td>Ionized Gases</td>
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**Communications, Sensors and Software**

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<tr>
<th>Course Code</th>
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<tr>
<td>16.343</td>
<td>Spacecraft and Aircraft Sensors and Instrumentation</td>
</tr>
<tr>
<td>16.36</td>
<td>Communication System Engineering (can be taken as G-level)</td>
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<tr>
<td>16.37J</td>
<td>Data-Communication Networks</td>
</tr>
<tr>
<td>6.442</td>
<td>Optical Communications and Networks</td>
</tr>
<tr>
<td>16.863</td>
<td>System Safety</td>
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<tr>
<td>6.852</td>
<td>Distributed Algorithms</td>
</tr>
<tr>
<td>6.661</td>
<td>Receivers, Antennas and Signals</td>
</tr>
<tr>
<td>6.630</td>
<td>Electromagnetics</td>
</tr>
<tr>
<td>6.631</td>
<td>Optics and Photonics</td>
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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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* Director of the MIT Space Systems Laboratory (SSL)

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