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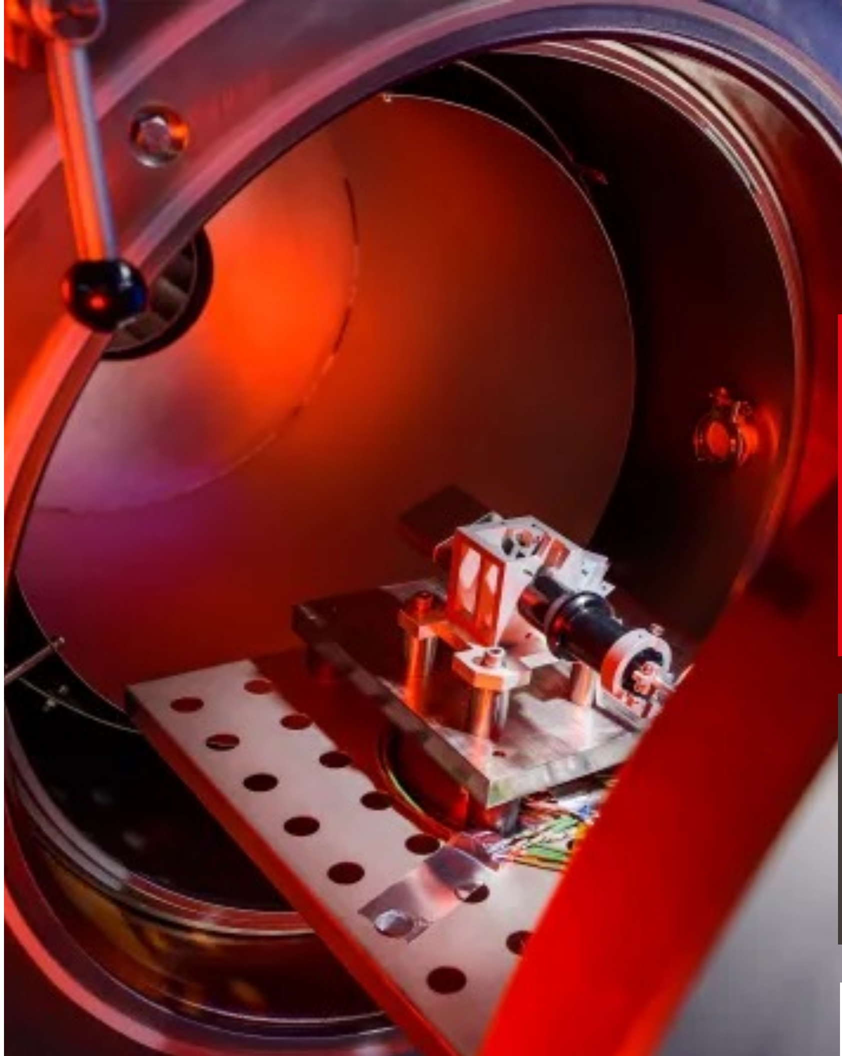


https://www.beyondgravity.com/en/satellites/platform-mechatronics

MICRO 372 - Advanced Mechanisms for Extreme Environments

Chapter 1 Introduction

Florent Cosandier

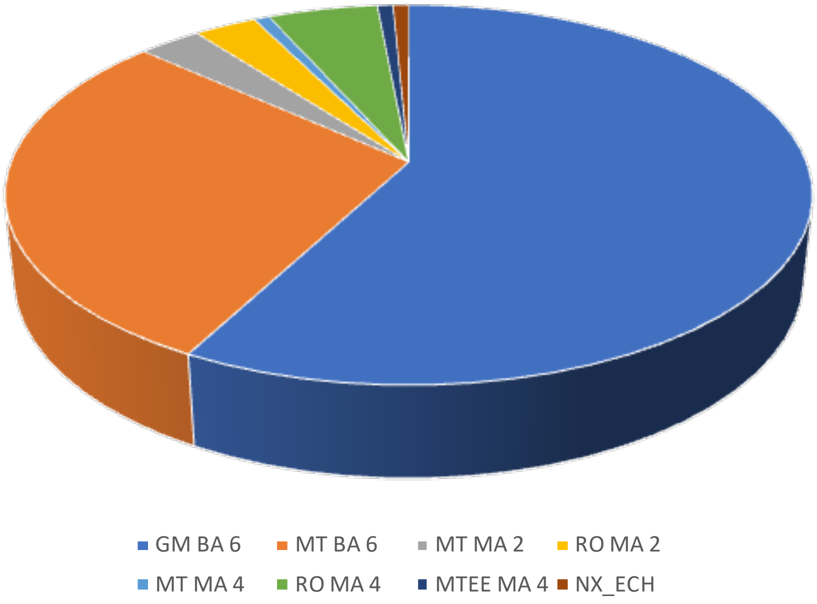
École polytechnique fédérale de Lausanne

Course organisation

MICRO-372 / 3 ECTS

- **Teacher**: Florent Cosandier
- **Language**: course material in english, oral presentation in french
- **Curriculum**:

GM BA 6	78
MT BA 6	39
MT MA 2	4
RO MA 2	4
MT MA 4	1
RO MA 4	7
MTEE MA 4	1
NX_ECH	1



- **Course**: 2 hours weekly x 13 weeks
- **Exercises**: 1 hour weekly x 13 weeks
- **Room** : CM 1 4

Meet the teacher – Florent Cosandier

- M.Sc. in Microengineering EPFL (2007)
- Ph.D. thesis in Manufacturing Systems and Robotics EPFL (2013)
- Postdoctoral Scientist – METAS (2013-2014)
- Expert R&D Engineer – CSEM (2014-2022)
- Research Associate at Instant-Lab – EPFL (2022-now)

- Author or coauthor of 30+ publications
- Author or coauthor of 8 patents
- Coauthor of 1 book

- Contact: florent.cosandier@epfl.ch

Meet the assistants team

- Mehmet Furkan Dogan

- Sloan Zammouri

- Adrien Chevallier

Course plan

1.	**Introduction**	(1 hour)
2.	**Application** fields and examples	(3 hours)
3.	Operating **environments** and associated constraints	(4 hours)
4.	Advanced mechanisms **design**	(4 hours)
5.	Advanced mechanisms **analysis**	(4 hours)
6.	Mechanisms **dynamic** aspects	(2 hours)
7.	**System** aspects	(1 hour)
8.	(Ultra-) High **precision**	(1 hours)
9.	Manufacturing, Integration and Assembly	(2 hours)
10.	**Characterization** and testing	(2 hours)
11.	Synthesis **examples**	(2 hours)

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Course agenda

Week	Day	Date	Month	Public holiday	Cours num.	Room	Hour 1 (15h15) - Lecture	Hour 2 (16h15) - Lecture	Hour 3 (17h15) - Exercises
8	Monday	17	February		1	CM 1 4	Ch. 1 - Introduction	Ch. 2 - Applications	Exo. 1
9	Monday	24	February		2	CM 1 4	Ch. 2 - Applications	Ch. 2 - Applications	Exo. 2
10	Monday	03	March		3	CM 1 4	Ch. 3 - Environments	Ch. 3 - Environments	Exo. 3
11	Monday	10	March		4	CM 1 4	Ch. 3 - Environments	Ch. 3 - Environments	Exo. 4
12	Monday	17	March		5	CM 1 4	Ch. 4 - Design	Ch. 4 - Design	Exo. 5
13	Monday	24	March		6	CM 1 4	Ch. 4 - Design	Ch. 4 - Design	Exo. 6
14	Monday	31	March		7	CM 1 4	Ch. 5 - Analysis	Ch. 5 - Analysis	Exo. 7
15	Monday	07	April		8	CM 1 4	Ch. 5 - Analysis	Ch. 5 - Analysis	Exo. 8
16	Monday	14	April		9	CM 1 4	Ch. 6 - Dynamics aspects	Ch. 6 - Dynamics aspects	Exo. 9
17	Monday	21	April	Easter Monday			Ch. 6 - Dynamics aspects	Ch. 6 - Dynamics aspects	Exo. 9
18	Monday	28	April		10	CM 1 4	Ch. 7 - System aspects	Ch. 8 - High precision	Exo. 10
19	Monday	05	May		11	CM 1 4	Ch. 9 - Manufacturing	Ch. 10 - Characterization	Exo. 11
20	Monday	12	May		12	CM 1 4	Rehearsal + evaluation	Rehearsal	Rehearsal
21	Monday	19	May		13	CM 1 4	Ch. 11 - Synthesis Examples	Ch. 11 - Synthesis Examples	-
22	Monday	26	May						

Learning Objectives (official)

What you will be able to do at the end of the course:

- Formulate functional and **environmental specifications** based on established **requirements**.
- Tackle the **design of high-precision mechanisms** compatible with the constraints (material compatible with vacuum/radiation, thermal effects, magnetic effect, shocks, vibrations, wear, degassing, emission of particles, etc.) relating to the operating environments.
- **Identify the analyzes required** to carry out the critical sizing of a mechanism.
- **Predict the performances** of a given mechanism and develop **experimental protocols** to validate them experimentally.
- Evaluate **the life duration of a mechanism**, establish maintenance and dismantling procedures.

Learning Objectives (additional)

At the end of the course, you will:

- Be at ease with **advanced mechanical engineering concepts**
- Be familiar with the various **fields of application** where **precision mechanisms** are used
- Have a broader “**engineering culture**”
- See the **concrete usefulness** of the **theoretical tools** you learn to use
- Understand typical **project workflows** in the **space sector**, among others
- Stimulate your **creative spirit** to **imagine innovative and high-performance mechanisms**

Recommendations for optimal learning

- **Class attendance**: Make sure you regularly attend **ex-cathedra classes** and **practical exercise** sessions. Class attendance is essential to grasp key concepts and ask live questions.
- **Active participation**: Engage in class discussions, **ask questions** and share your ideas. Active participation can deepen your understanding of topics and demonstrate your commitment.
- **Teamwork**: During group practical's, **work effectively with your classmates** to build on each other's strengths and solve problems collectively.
- **Ask questions**: Don't hesitate to ask your teacher, assistants or classmates questions if something isn't clear. Seeking **clarification strengthens your understanding**.
- **Do exercises**: Devote time to solving practical exercises to **put theoretical concepts into practice** and develop your problem-solving skills.
- **Use additional resources**: Explore books, articles and online resources to **deepen your understanding** of topics of particular interest to you.
- **Exam preparation**: Start preparing early for intermediate and final exams by regularly reviewing material, solving problems and **succeed with it**!

Exercises sessions information

- Exercises are done **in room CM 1 4** on your **personal computer.**
- We encourage you to do exercises **in pairs.**
- You need to connect to the following platform:

VDI.EPFL.CH

- Using **VMware Horizon Client** or **your browser.**
- Connect to the **STI-Windows10** virtual machine.
- Exercises are performed partly on **MATLAB** and partly on **COMSOL.**
- **Data files** are **downloaded** at the beginning of the exercise session via **Moodle.**
- It is essential to **save the files at the end of the exercise session (e.g. on MyNAS)**, as **everything is deleted from the virtual machine when the session is closed.**
- **MyNAS** : files0.epfl.ch, files1.epfl.ch, …, files9.epfl.ch (number is SCIPER modulo 10).
  - E.g. smb://files5.epfl.ch/dit_files5_indiv/data/cosandie/ or \\files8.epfl.ch\dit_files8_indiv\data
- **Copy and paste the file** to and from the **VDI platform** may works also..

Exam during exam session, no mid-term

Format:

- **Multiple choice questions (25%)**
- **Problems to solve, calculations (75%)**
- **No open questions**

Details:

- **No form** to prepare
- **Form** with necessary formulas will be **provided**
- **MCQ** will be counted as follows:
  - **Correct answer : +1**
  - **Wrong answer: -0**

Course within MT Cursus

Bachelor Microtechnique

	Fundamentals	Programming	Electronics	Mechanics	Materials	Optics	Micro-Nano / Advanced Manufacturing	SHS
Propedeutical	Algèbre linéaire Analyse I, II Phys. Gén. mécanique / Thermodynamique Design of Experiments	Information, calcul et communication Programmation orientée projet	Electrotechnique I, II	Construction mécanique I, II	Materials, from chemistry to properties			2 ECTS
2nd year	Analyse III, IV Analyse numérique Physique générale: Electromagnétisme Eléments de statistiques pour les data sciences	Microcontrôleurs Systèmes logiques	Electronique I, II	Mise en œuvre des matériaux I, II Conception de mécanismes I, II Stage d'usinage				4 ECTS
3rd year	Signaux et systèmes I, II	Automatique et commande numérique Systèmes embarqués et robotique	Capteurs Circuits et systèmes électroniques Actionneurs et systèmes électromagnétiques I, II			Ingénierie optique	Manufacturing technologies Microfabrication technologies Microfabrication practicals	4 ECTS
Optional Ba5-6	Physique des Composants Semiconducteurs La science quantique – une vision singulière	Software architecture	Introduction to Bioengineering Wireless sensor practicals	Advanced mecanisms for extreme environments			Advanced Microfabrication practicals	

Course topics overview

Advanced mechanisms for extreme environments

Applications
- Aerospace
- Astrophysics
- Metrology
- Biomedical
- Horology
- Robotics
- MEMS
- Nuclear physics
- Big Science

Implementation
- Flexures
- Traditional

Ultra-high precision
- Perturbation sources
- Measurement Instruments
- Calibration

Design & analysis
- Structural calculation
- Geometrical models
- Materials
- Sizing
- COTS selection
- Kinematic analysis
- Static FEA
- Modal FEA

Characterization
- Functional
- Lifetime
- Thermal
- Environmental

System aspects
- Actuators
- Sensors
- Control

Environments
- Vacuum
- Cryogenic
- High temperature
- Radiative
- Sterile
- Magnetism
- In vivo
- Vibrations
- Microgravity

Applications VS environments matrix

	Vacuum	Cryogenics	High temperature	Radiations	Magnetics	Sterile	In vivo	Vibrations	Micro-vibrations	Micro-gravity	Dust	Outgasing
Space	x	x	x	x	x	x		x	x	x	x	x
Astrophysics	x	x						x	x		x	x
Robotics	x	x	x	x	x	x	x	x	x	x	x	x
Metrology	x				x			x	x			
Biomedical						x	x					
Watch					x			x			x	
MEMS	x							x			x	
Nuclear physics	x	x	x	x	x							x

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Course highlight topics

Space

newsweek.com

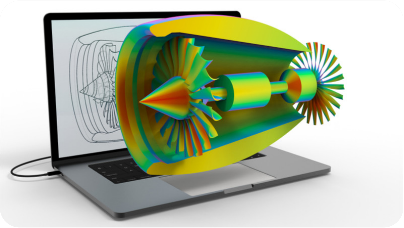
Compliant mechanisms

monochrome-watches.com

Watchmaking

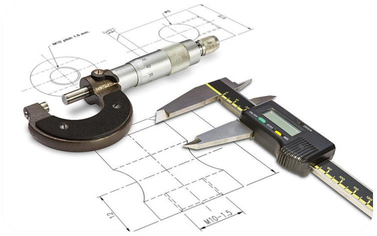
monochrome-watches.com

FEM/FEA



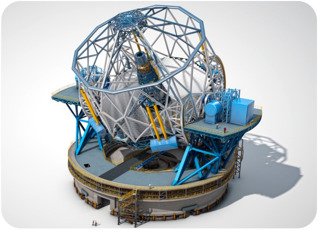
imeche.org

Metrology & calibration



qualitymag.com

Big Science

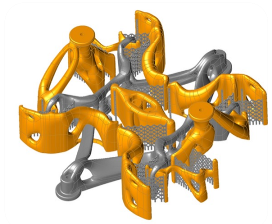


wikipedia.org

Dynamics

fanuc.eu

Topology optimization



csem.ch

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Specific engineering knowledge VS overall scientific culture

Engineering knowledge ⟷ Scientific culture

Design and analysis

Kinematics
Geometrical models
Optimization
FEM/FEA
…

Methodology

Ideation/brainstorming
Trade-off
Risk analysis
Preliminary design
Detailed design
…

Environments and constraints

Vacuum
Cryogenics
Radiative
Magnetics
Sterile
Vibrations
Gravity
…

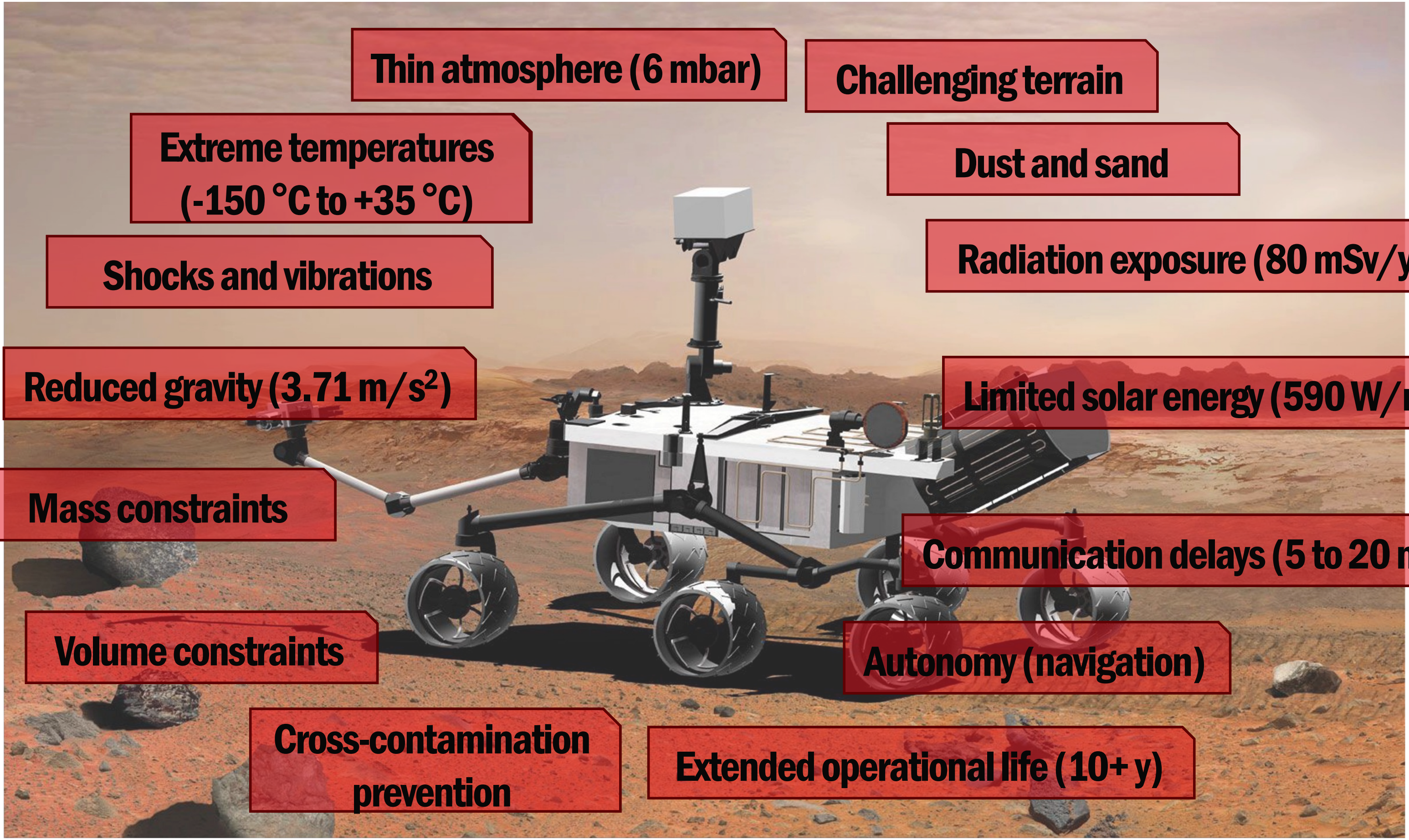
Topics

Optics
Outgassing
Materials
Dynamics
Damping
Ultra-high precision
System aspects
…

Applications and examples

Space
Metrology
Watch making
Biomedical
…

Environmental and design constraints example: Mars rover



britannica.com

Extreme environment introduction

Definition (wikipedia):

An **extreme environment** is a habitat that is **considered very hard to survive** in due to its considerably **extreme conditions** such as **temperature, accessibility to different energy sources or under high pressure.**

For an area to be considered an extreme environment, it must contain certain conditions and aspects that are considered very hard for other life forms to survive. **Pressure conditions** may be extremely high or low; high or low **content of oxygen** or **carbon dioxide in the atmosphere**; high **levels of radiation**, **acidity**, or **alkalinity**; **absence of water**; water containing a high **concentration of salt**; the presence of **sulphur**, **petroleum**, and **other toxic substances**.

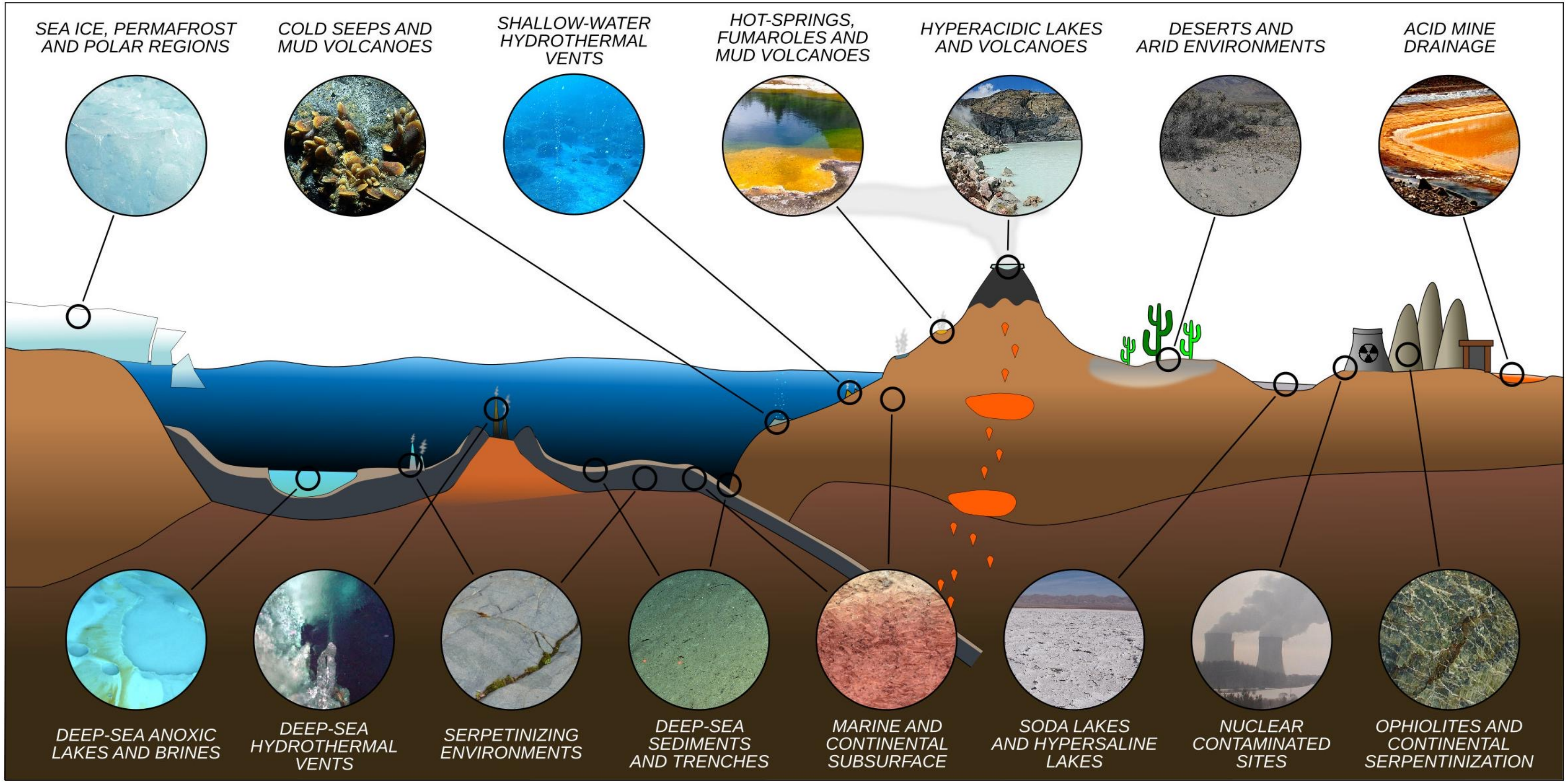
Examples of extreme environments include the **geographical poles**, **very arid deserts**, **volcanoes**, **deep ocean trenches**, **upper atmosphere**, **outer space**, and **the environments of every planet in the Solar System except the Earth**. […]

Extreme environment introduction

Physical environments can encompass such **components**:

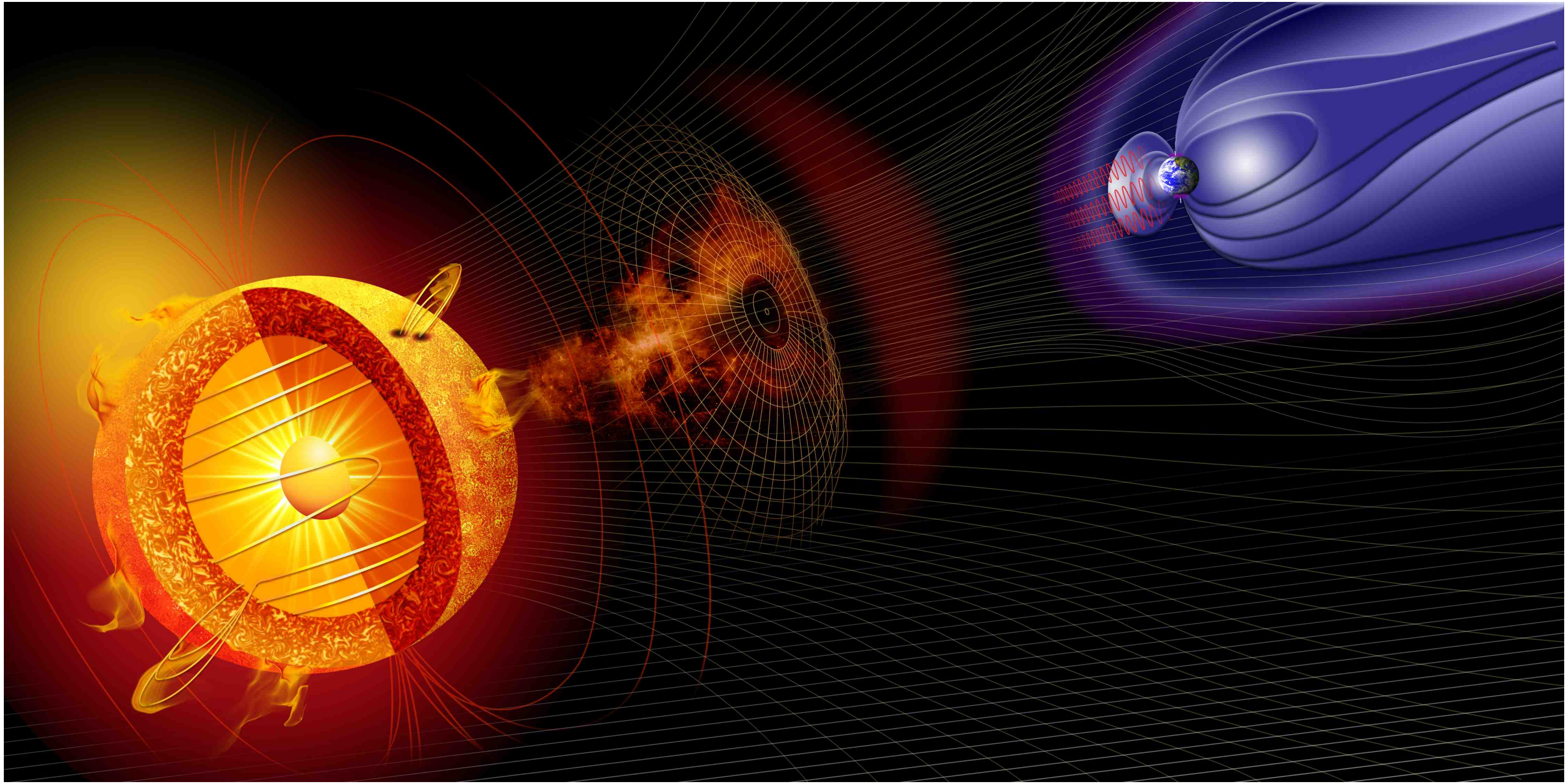
1.	**Atmospheric composition**	Air and gases, pollutants and contaminants
2.	**Pressure**	10^{-12} mbar -> 1000+ bar
3.	**Water, Soil**	Hygrometry, pH
4.	**Light**	0 -> 10^5 lux
5.	**Heat and Temperature**	0 K -> several thousand K
6.	**Gravity**	0 g -> 2.5 g (on Jupiter)
7.	**(Electro)magnetic fields**	0 T -> 8 T (at CERN)
8.	**Vibrations**	Many kinds of vibrations
9.	**Radiations**	0 mSv -> 50 Sv (Chernobyl core – 10 minutes)
10.	**..**	

Extreme environment introduction: terrestrial examples



N. Merino et al. *Living at the Extremes: Extremophiles and the Limits of Life in a Planetary Context*, Front. Microbiol., 15 April 2019, Sec. Extreme Microbiology Volume 10 - 2019 I https://doi.org/10.3389/fmicb.2019.00780

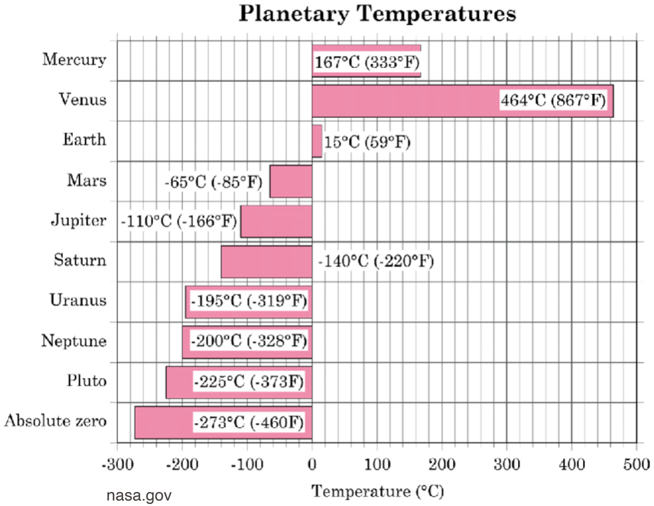
Extreme environment introduction: space example



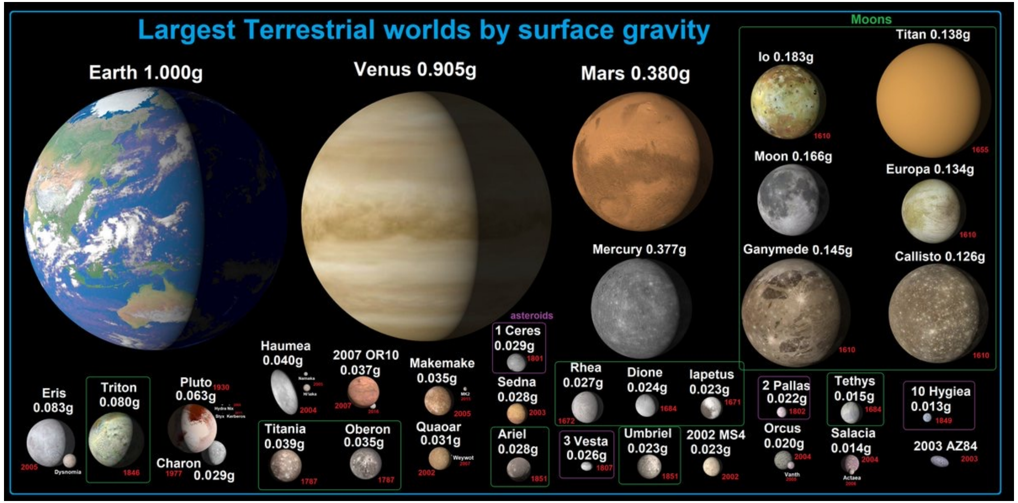
usgs.gov

The solar wind streams off of the Sun in all directions at speeds of about 400 km/s

Extreme environment introduction: planetary conditions

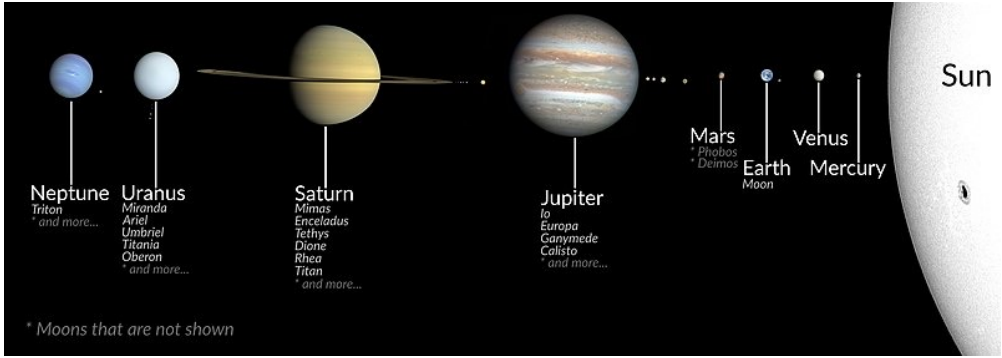


nasa.gov



imgur.com

Planet	Acceleration due to gravity $\left(\frac{m}{sec^2}\right)$
Mercury	3.6
Venus	8.9
Earth	9.8
Mars	3.8
Jupiter	26.0
Saturn	11.1
Uranus	10.7
Neptune	14.1



Advanced mechanisms introduction

Definition of a **mechanism**:

- A system of mutually adapted **parts working together in a machine** often characterized by their ability to **transmit, convert, or control motion, force, energy, or information** to achieve a desired outcome. Mechanisms can range **from simple tools and machines to complex systems** that involve intricate interactions between multiple components.

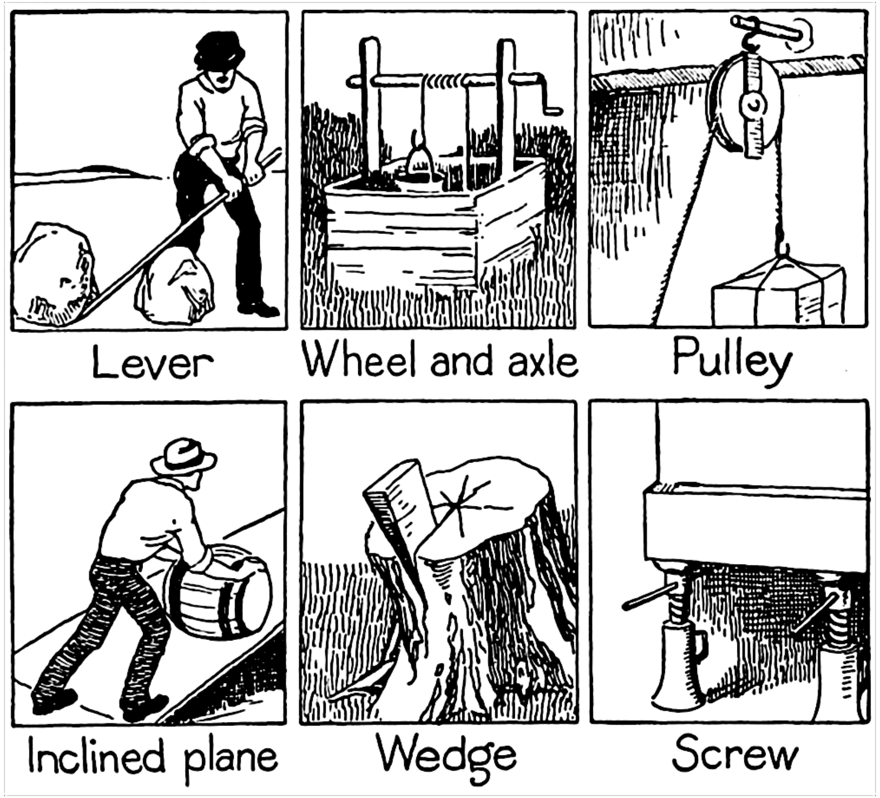
Definition of an **advanced mechanism**:

- An advanced mechanism, in the context of mechanical engineering, refers to a **complex and sophisticated system** of **interconnected components and parts** designed to perform **intricate tasks**, exhibit **precise motions**, or achieve **specialized functions**. These mechanisms often involve intricate combinations of **gears**, **linkages**, **cams**, **levers**, and other **mechanical elements that work together** to accomplish tasks that go beyond the capabilities of simple mechanisms.

- Examples of advanced mechanisms in mechanical engineering include **robotic arms** with multiple degrees of freedom, intricate **gear trains** in high-performance machinery, complex **linkage systems** in automotive suspensions, and **precision mechanisms** in scientific instruments.

Advanced mechanisms introduction

- Simple mechanisms (simple machines) examples

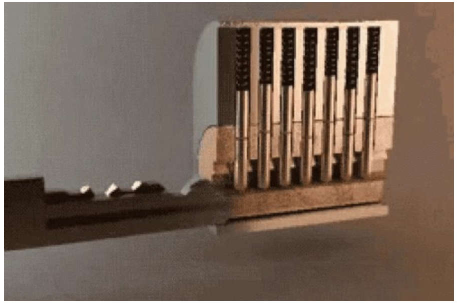


en.wikipedia.org

Advanced mechanisms introduction

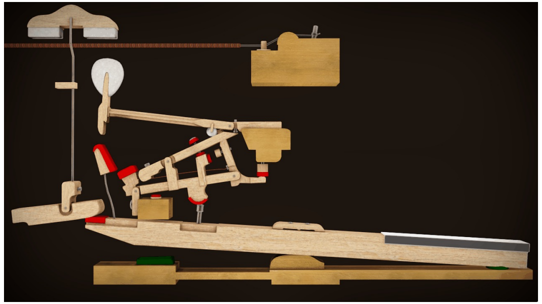
- Mechanisms examples

Door lock mechanism



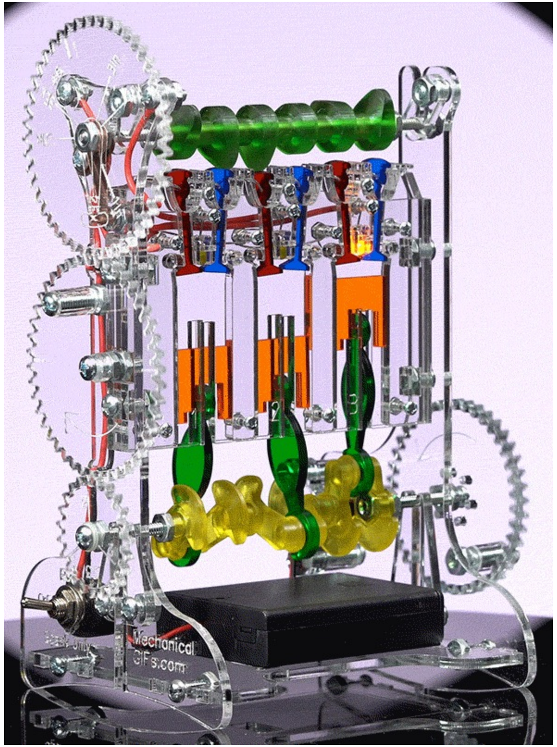
tenor.com

Piano key mechanism



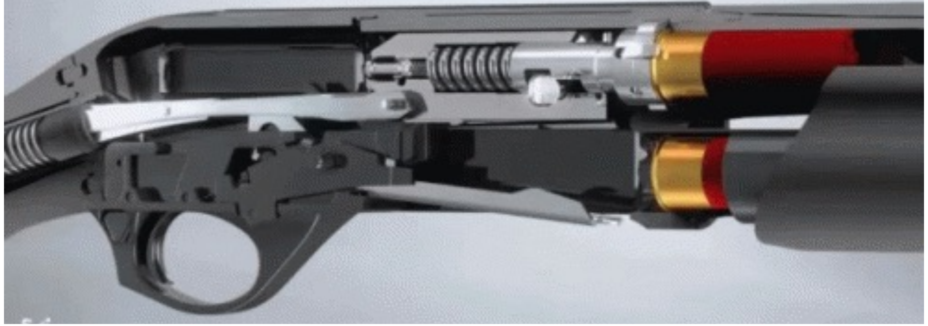
pianostreet.com

Combustion Engine



mechanicalgifs.com

Shot gun mechanism

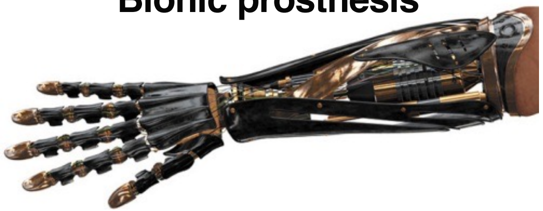


tenor.com

Advanced mechanisms introduction

- Advanced mechanisms examples

Bionic prosthesis

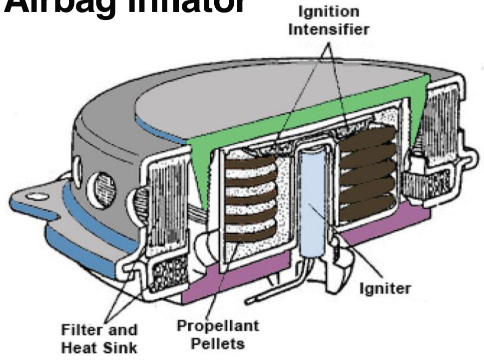


starwars-holonet.com

Industrial robot

zoneindustrie.com

Airbag inflator

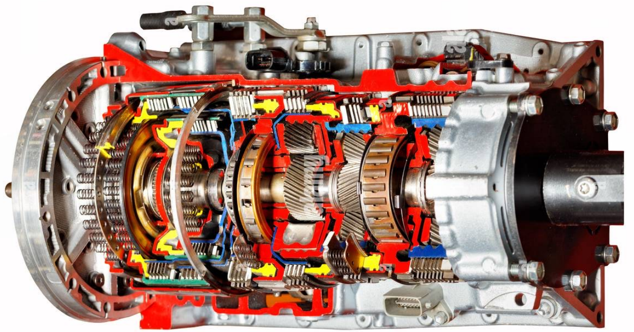


islandpyrochemical.com

Horological complication

minutemontre.fr

Automatic transmission



alamyimages.fr

Advanced mechanisms introduction

Advanced mechanisms in mechanical engineering typically exhibit **characteristics** such as:

1. **Precision:** They are designed with high accuracy and tight tolerances to ensure consistent and reliable performance.
2. **Complex motion:** They can generate complex or specialized motions, like harmonic oscillatory movements, that are not easily achievable with basic mechanisms.
3. **Multiple degrees of freedom:** They can provide more than the basic translational or rotational movements, allowing for more versatile and intricate motions.
4. **Automation and control:** Advanced mechanisms often integrate with control systems, sensors, and actuators to enable automation and precise control over their operations.
5. **Incorporation of advanced materials:** They may incorporate specialized materials such as composites, alloys, or high-performance polymers to enhance strength, durability, and overall functionality.
6. **High efficiency:** These mechanisms are often designed to minimize energy loss and friction, maximizing the efficiency of their operations.
7. **Specialized applications:** They are developed for specific applications where precision, complexity, and specialized functionality are required, such as robotics, aerospace systems, medical devices, and more.

Advanced mechanisms introduction: sources of error

Common sources of error in precision mechanisms:

1. **Incorrect tolerances and fits**
2. **Wear and degradation**
3. **Friction and frictional forces**
4. **Bending and deformation**
5. **Mechanical instability**
6. **Thermal effects**
7. **Sensor errors**
8. **Electromagnetic interference**
9. **Design errors**
10. **Manufacturing defects**

Minimizing and managing these sources of error are crucial challenges in designing, manufacturing, and using advanced precision mechanisms. Techniques for **precise design**, **appropriate materials**, and **sophisticated control** and **calibration methods** are employed to **reduce these errors** and ensure accurate and reliable operation of the mechanism.

Advanced mechanisms introduction: compliant mechanisms

A compliant mechanism is a flexible mechanism that achieves **force** and **motion transmission** through **elastic body deformation**.

It gains some or all its motion from the **relative flexibility** of its members rather than from rigid-body joints alone.

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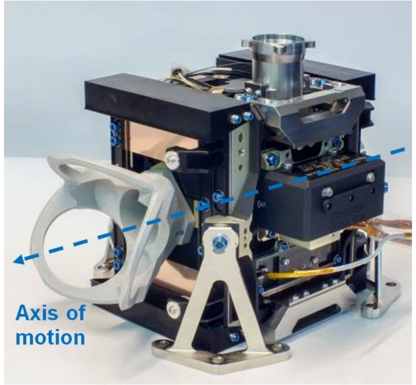
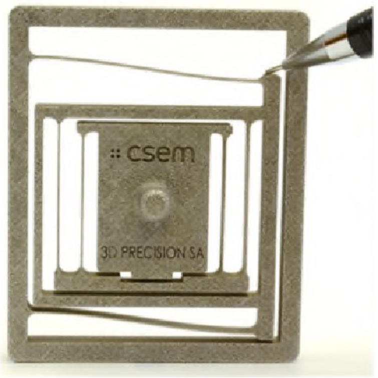
Zenith DEFY LAB





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Advanced mechanisms introduction: compliant mechanisms

Advantages of compliant mechanisms:

- No solid friction
- No need for lubrication
- No wear
- No backlash
- No hysteresis
- Infinite lifetime
- High quality factor and low energy losses
- Possibly monolithic parts
- Ability to be miniaturized

Challenges of compliant mechanisms:

- Restoring force
- Limited stroke
- Sensitive to manufacturing
- Complex modelling

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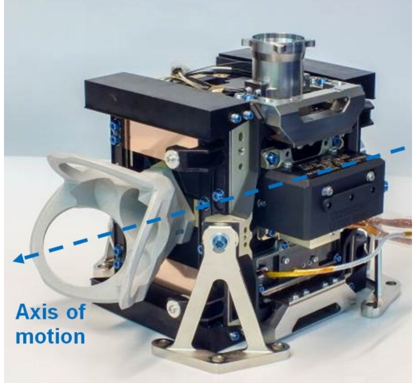
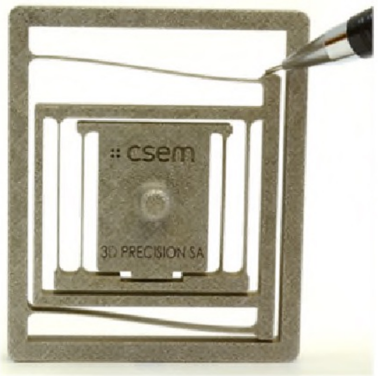


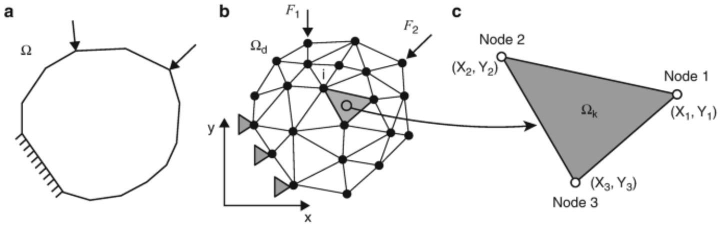


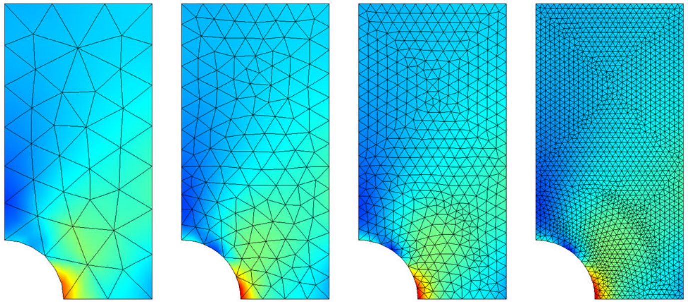
CSEM

All of that makes **flexures** a **very suitable solution for mechanisms in extreme environments!!**

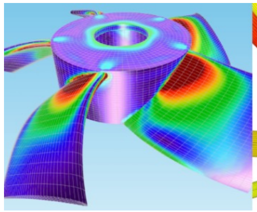
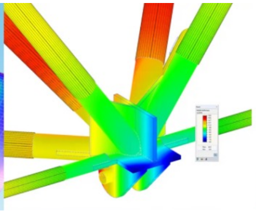
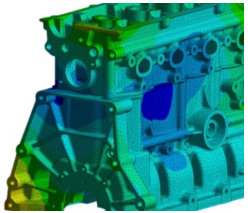
Advanced mechanisms introduction: Finite Element Analysis

- **Finite Element Methode** (FEM) is also named **Finite Element Analysis (FEA)**
- **FEA** is used to **validate analytical models** (or replace them)
- **Typical steps** of the **Finite Element Analysis** involve:
  - **Discretization** of the problem domain into finite elements and nodes
  - Formation of **element equations** by local approximation
  - **Assembly** of element equations to **arrive structural equations**
  - Modification and **solution** of emerging equations with **boundary conditions**
  - **Interpretation of results**





comsol.com

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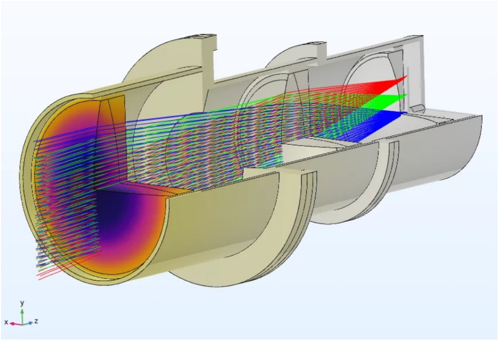
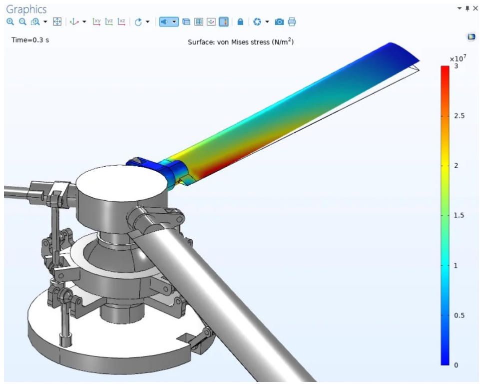
Advanced mechanisms introduction: COMSOL multiphysics

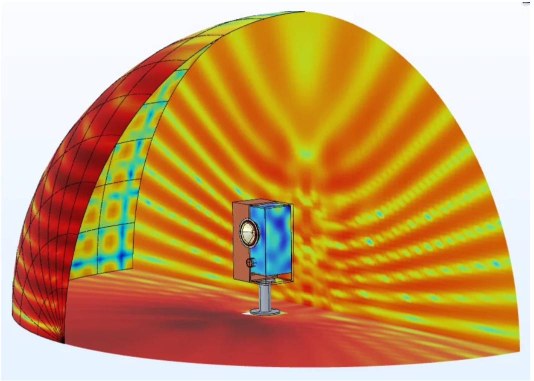
- Multiple physics can be simulated
- It is possible to couple the different physics through multiphysics coupling
- Well suited to calculate large mechanical deformations
- Survey : who experienced COMSOL?



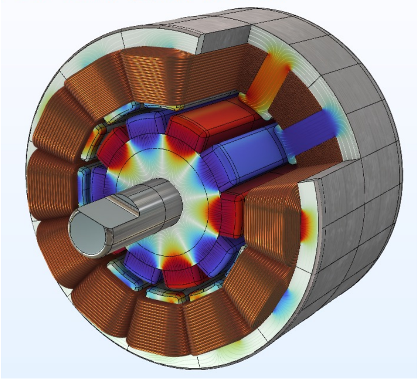
Geometric optics is used to model the propagation of electromagnetic waves



Stress and deformation of helicopter blades, caused by rotation and dynamic lift force



Vibroacoustic analysis of a loudspeaker



Model of a permanent magnet motor with several stator coils.

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Chapter summary

- Course logistics
- Course content overview
- Introductive example – Mars rover
- Extreme environment introduction
- Advanced mechanisms introduction
- Compliant mechanisms
- Finite Element Analysis