University of Trento
Trento, Italy

Advanced Robotics with Applications to Space Exploration

Syllabus

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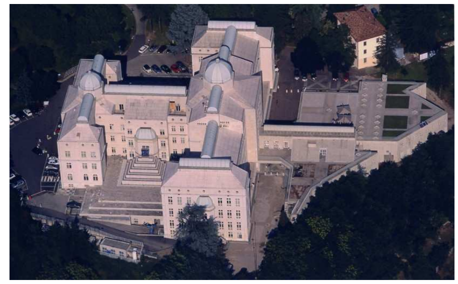

Course Description: A 20 hour course for advanced study of robot design with application to space exploration. An optional course project involves writing a concept paper for the design of a semi-autonomous robot for exploring one of the planets or moons in our solar system.

LECTURE	TOPICS	RECOMMENDED READINGS
"SOLAR SYSTEM" PPT PDF	Terrestrial planets and moons	
"ROVERS IN SPACE" PPT PDF	**1971** Lunar Rover (LRV) **1996** Mars Pathfinder *Sojourner* **2004** Mars Exploratory Rovers *Spirit & Opportunity* **2011** *Mars Science Lab* **2016** Mars *ExoMars*	[3, 34, 35] [3, 4] [3]
"EUROPA" PPT PDF	**1977** *Voyager 1 & 2* **1989** *Galileo* **2020** *Europa Jupiter System Mission* **2040? Europa Rover** (Optional course project)	[4] [4, 8] [2] [6, 8, 29]
"**ROVER MECHANICS**" PPT PDF	Gravity effects, Manned vs. unmanned, Biological inspirations, Mobility, Suspension systems, Wheels and traction, Maneuverability, stability, and controllability	[1, 11, 33, 34, 35]
"DELIVERY SYSTEMS" PPT PDF	Launch, landing, deployment, Shielding and hardening for heat, cold, radiation, and vibration	[3, 4, 9, 28]
"POWER" PPT PDF	Electrical power demand, generation, and storage	[3]
Below are historically the main areas of research for Dr. Wunderlich and his students		
"ARM DESIGN" PPT PDF	Manned vs. unmanned tasks, instrument deployment vs. dexterous manipulation, Redundant and Hyper-redundant manipulators, Psuedo-inverse velocity-control **PATH-PLANNING**, Attractive poles, Repelling-fields, Creative use of null-space, Heuristic search, DOF minimization, *"**C**onsumption **O**f **A**vailable **R**edundancy (COAR),"* Rapid prototyping	[5, 14, 15]
"SENSORS & NAVIGATION" PPT PDF	**PATH-PLANNING**, Dead reckoning, Celestial navigation, Mapping, Positioning, Steering, Sensors, Tele-operation, Remote communication, Local and global path-planning, Obstacle avoidance, Systems integration, Autonomy	[1, 3, 11, 12, 22, 18, 31, 32, 33, 36, 37]
"UAVS, UUV'S, AND SWARMS" PPT PDF	Unmanned Aerial Vehicles (UAV's); Unmanned Underwater Vehicles (UUV's) Networked swarms	[30]
"COMPUTING" PPT PDF	Simulations, real-time control , Embedded systems, Micro controllers, Microprocessors, PC's, Workstations, Super computers, Quality control through *"Controlled Randomness"*	[17, 19, 25, 26, 27, 28, 37]
"MACHINE INTELLIGENCE" PPT PDF	Symbolic AI vs. connectionist architectures, Biologically-inspired vs. behavioral / mathematically-inspired neural networks, Neurocomputer design, Autonomy	[10, 13, 16]

Prerequisites

- Registration as a University of Trento Ph.D. student (or permission from U. of Trento)
- Completion of an introductory course in Robotics (or permission of your Ph.D. advisor)

Lecture Format

- PowerPoint and web-posted lectures
- Notes written on board
- Group discussion of book chapters and papers

2009 Course Project Options

(A) Any project related to the content of this course and which is approved by your Ph.D. Advisor. Those who complete the project will receive more credit for the course. The amount of credit received must be agreed upon by your Ph.D. advisor.

or

(B) Conceptual Design of a Europa Rover

- Those who complete the project will receive more credit for the course
- The amount of credit receive must be agreed upon by your Ph.D. advisor
- Write a concept paper which relates a rover design to course lectures and readings.
- Paper should be formatted according to IEEE or ASME conference paper standards
- Although course research is not expected to immediately produce a publication, selected papers may be identified by Dr. Wunderlich or Ph.D. advisor as candidates for continued research and potential future publication
- Students should elaborate on aspects of design related to their area of expertise, however all aspects of design should be discussed
- Papers are to be submitted to Dr. Wunderlich (via email: wunderjt@etown.edu) within the two weeks following the last day of class
- The following data, project design goals, and assumptions should be included in the "Introduction" section of the paper:

The mission objective is to explore an ocean confirmed in 2025 to be under the ice of Europa. Assume your launch is scheduled for 2040.

Also assume one of the following:

1) The ***Europa Jupiter System Mission*** [2] scheduled for launch in 2020 discovers some very thin patches of ice (less than 200 meters thick) created by localized sub-surface thermal anomalies.
2) A mission concurrent to yours (but designed by others) has created craters on Europa's surface that have frozen over with approximately 200 meters of ice; but assume the ice will quickly freeze much thicker -- and therefore a rapid execution of all mission operations is critical.

Your rover must be able to:

- Maneuver on the flat icy surface of Europa *(Assume some mobility is required even though main objective is getting below surface)*
- Drill through at least 200 meters of ice
- When liquid water is reached, either:
  (1) Act as an Unmanned Underwater Vehicle's (UUV), or
  (2) Deploy 100 very small networked UUV's (i.e., a "Swarm"). Assume they are only 10 centimeters long.
- Communicate with the UUV's if option (2) above is chosen
- Communicate with a base station that is also communicating with several orbiters, and earth. The base station is also assumed to be running a concurrent simulation to the rover's real-time code and will be building an environmental map simulation of the region of Europa being explored. This simulation information should also be communicated back to the rover, and then to UUV's if option (2) above is chosen; this is to help with exploration and preservation of the rover.
- Optionally, control a hyper-redundant manipulator attached to the rover to aid with exploration, digging, and/or deployment of small UUV's
- Withstand the extremely cold temperatures (-143C, -225F max), [9]
- Power itself by some energy source other than the sun since incident solar radiation reaching Europa is minimal; propose a means of powering the rover.

Assume the launch vehicle and delivery system are designed by others. Begin your rover's trek on the surface by assuming that a successful orbiter and base station have been deployed; you may assume your rover is delivered to the surface by a different method (and location) than the base station. When estimating vehicle weight and maximum payload, consider that Europa's gravity is only 13.5% of Earth's.

Facts on Europa [8]:

Discovery:	Jan 7, 1610 by Galileo Galilei
Diameter (km):	3,138
Mass (kg):	4.8e22 kg
Mass (Earth = 1)	0.0083021
Surface Gravity (Earth = 1):	0.135
Mean Distance from Jupiter (km):	670,900
Mean Distance From Jupiter (Rj):	9.5
Mean Distance from Sun (AU):	5.203
Orbital period (days):	3.551181
Rotational period (days):	3.551181
Density (gm/cm^3)	3.01
Orbit Eccentricity:	0.009
Orbit Inclination (degrees):	0.470
Orbit Speed (km/sec):	13.74
Escape velocity (km/sec):	2.02
Visual Albedo:	0.64
Surface Composition:	Water Ice

- The smallest of the four Galilean moons.
- The 6th largest satellite in the solar system.
- Slightly smaller than our Moon.
- The smoothest object in the solar system.
- A mostly flat surface with nothing exceeding 1 km in height.
- Surface is about 5 times brighter than our Moon.
- Two types of terrains on icy crust:
    - Mottled, brown or gray in color and consisting of mainly small hills
    - Large smooth plains criss-crossed with a large number of cracks
        - Some curved and some straight
        - Some extend for thousands of kilometers
- Cracked surface appears remarkably similar to that of the Arctic Ocean on Earth.
- There are very few craters, particularly large craters.
- The lack of craters indicates a young age for the surface.
    - Perhaps as young as 30 million years old.
- The inner core is suspected to be iron-sulfur, similar to that of Io.
- A tenuous atmosphere of oxygen has been detected.

As of 2009, most of the scientific community agrees that there is almost certainly a liquid ocean beneath the icy surface of Europa, and that the potential for microbial life there exists; see [29] and the many recent talks posted on the website for the ***International Workshop on Europa Lander: Science Goals and Experiments***, February 9-13, 2009, Moscow, Russia.

Readings

Excerpts from the following will be distributed and discussed in lecture:

[1] R. Siegwart and I. Nourbakhsh, ***Autonomous mobile robots***, Massachusetts Institute of Technology, 2004. (ISBN: 026219502X)

[2] K.. Clark, A. Stankov, R. Pappalardo, M. Blanc, R. Greeley, J.P.Lebreton , ***Europa Jupiter System Mission; A Joint Endeavour by ESA and NASA***, NASA Report, January 16, 2009.

[3] Anthony H. Young, ***Lunar and planetary rovers: the wheels of Apollo and the quest for mars***, Springer; 1 edition, August 1, 2006. (ISBN: 0387307745)

[4] Paolo Ulivi and David M. Harland, ***Robotic exploration of the solar system: part II: hiatus and renewal, 1983-1996***, Praxis; 1 edition, November 25, 2008. (ISBN: 0387789049)

[5] S. . B. Niku, ***Introduction to Robotics: Analysis, Systems, Applications***, Prentice Hall, July 30, 2001. (ISBN: 0130613096)

[6] R. Greenberg, ***Unmasking Europa: The search for life on jupiter's ocean moon***, Springer; 1 edition, August 19, 2008. (ISBN: 0387479368)

[7] R. Audouze (Editor), G. Israel (Editor), ***The cambridge atlas of astronomy,*** Cambridge University Press; 3 edition, November 28, 1994, (ISBN: 0521434386)

[8] Website: ***Europa, a Continuing Story of Discovery*** [**http://www2.jpl.nasa.gov/galileo/europa/**].

[9] Website: ***JPL Photojournal*** [**http://photojournal.jpl.nasa.gov/catalog/PIA01144**].

[10] Wunderlich, J.T. (2008). **Two single-chip neurocomputer designs; one bottom-up, one top-down.** *(invited journal paper in peer-review)*

[11] Painter J. and Wunderlich, J.T. (2008). **Wunderbot IV: autonomous robot for international competition.** In *Proceedings of the 12th World Multi-Conference on Systemics, Cybernetics and Informatics: WMSCI 2008, Orlando, FL*: (pp. 62-67).

[12] Coleman, D. and Wunderlich, J.T. (2008). **O^3: an optimal and opportunistic path planner (with obstacle avoidance) using voronoi polygons.** In *Proceedings of IEEE the 10th international Workshop on Advanced Motion Control, Trento, Italy.* vol. 1, (pp. 371-376). IEEE Press.

[13] Wunderlich, J.T. (2004). **Top-down vs. bottom-up neurocomputer design.** In *Intelligent Engineering Systems through Artificial Neural Networks, Proceedings of ANNIE 2004 International Conference, St. Louis, MO.* H. Dagli (Ed.): Vol. 14. (pp. 855-866). ASME Press. [*"Novel Smart Engineering System Design Award, 2nd runner-up best paper"* from over 300 submissions],

[14] Wunderlich, J.T. (2004). **Simulating a robotic arm in a box: redundant kinematics, path planning, and rapid-prototyping for enclosed spaces.** In *Transactions of the Society for Modeling and Simulation International*: Vol. 80. (pp. 301-316). San Diego, CA: Sage Publications.

[15] Wunderlich, J.T. (2004). **Design of a welding arm for unibody automobile assembly.** In *Proceedings of IMG04 Intelligent Manipulation and Grasping International Conference, Genova, Italy,* R. Molfino (Ed.): (pp. 117-122). Genova, Italy: Grafica KC s.n.c Press.

[16] Wunderlich, J.T. (2003). **Defining the limits of machine intelligence.** In *Proceedings of IEEE SoutheastCon, Ocho Rios, Jamaica,* [CD-ROM]. IEEE Press.

[17] Campos, D. and Wunderlich, J. T. (2002). **Development of an interactive simulation with real-time robots for search and rescue.** In *Proceedings of IEEE/ASME International conference on Flexible Automation, Hiroshima, Japan*: (session U-007). ASME Press.

[18] Lister, M. and Wunderlich, J. T. (2002). **Digital communications for a mobile robot.** In *Proceedings of IEEE SoutheastCon,* Columbia, SC, [CD-ROM]. IEEE Press.

[19] Wunderlich, J.T. (2001). **Simulation vs. real-time control; with applications to robotics and neural networks.** In *Proceedings of 2001 ASEE Annual Conference & Exposition, Albuquerque, NM*: (session 2793), [CD-ROM]. ASEE Publications.

[20] Wunderlich, J.T. and Boncelet, C.G. (1996). **Local optimization of redundant manipulator kinematics within constrained workspaces.** In *Proceedings of IEEE Int'l Conference on Robotics and Automation*, Minneapolis, MN: Vol. (1). (pp. 127-132). IEEE Press.

[21] Wunderlich, J.T. (1996). **Optimal kinematic design of redundant and hyper-redundant** manipulators for constrained workspaces. *Ph.D. Dissertation*, University of Delaware.

[22] Wunderlich, J.T., S. Chen, D. Pino, and T. Rahman (1993). **Software architecture for a kinematically dissimilar master-slave telerobot**. In *Proceedings of SPIE Int'l Conference on Telemanipulator Technology and Space Telerobotics*, Boston, MA: Vol. (2057). (pp. 187-198). SPIE Press.

[23] Wunderlich, J.T., and Elias, J. (1993). **Design of an artificial dendritic tree VLSI microprocessor.** U.Del. research report, 1993.

[24] Wunderlich, J.T. (1992). **A vector-register neural-network microprocessor with on-chip learning.** *Masters Thesis*, Pennsylvania State University.

[25] Wunderlich, J.T. (1999). **Focusing on the blurry distinction between microprocessors and microcontrollers.** In *Proceedings of 1999 ASEE Annual Conference & Exposition, Charlotte, NC*: (session 3547), [CD-ROM]. ASEE Publications.

[26] Wunderlich, J.T. (2003). **Functional verification of SMP, MPP, and vector-register supercomputers through controlled randomness.** In *Proceedings of IEEE SoutheastCon, Ocho Rios, Jamaica,* M. Curtis (Ed.): (pp. 117-122). IEEE Press.

[27] Wunderlich, J.T. (1997). **Random number generator macros for the system assurance kernel product assurance macro interface**. Systems Programmer's User Manual for IBM S/390 Systems Architecture Verification, Poughkeepsie, NY.

[28] Patterson, R.L.. and Hammoud, Ahmad. (2004) **Reliability of Electronics for Cryogenic Space Applications Being Assessed**. *NASA Research and Technology 2004.*

[29] Pappalardo, R.T. (2006). **Europa: processes and habitability** (presentation)**.** Pasadena, CA: Jet Propulsion Laboratory, National Aeronautics and Space Administration

[30] Henderson, S., Shreshtha, S., Wunderlich, J.T. (2004). **A high speed AUV test platform** *(submitted to military conference)*.

[31] Painter, J. G. (2008). **Vision system for Wunderbot IV autonomous robot**. *Elizabethtown College research report.*

[32] Crouse, J. (2008). **The joint architecture for unmanned systems: a subsystem of the wunderbot 4**. *Elizabethtown College research report.*

[33] Painter, J. G., Coleman, D., Crouse, J., Yorgey, C., and Wunderlich, J.T. (2008) **Wunderbot 4 IGVC report**. *Judged and published on-line by IGVC.*

[34] Boeing Company and NASA (1971) **LRV operations handbook**. Document LS006-002-2H.

[35] Boeing Company and NASA (1971) **LRV operations handbook. appendix A performance data**. Document LS006-002-2H.

[36] Carsen, A., Rankin, J., Fuguson, D., and Stentz, A. (2007). **Global path planning on board the mars exploration rovers**. *In Proceedings of the IEEE Aerospace Conference, 2007. IEEE Press. (available at http://marstech.jpl.nasa.gov/publications/z02_0102.pdf)*

[37] Bajracharya, M., Maimone, M.W., and Helmick, D. (2008)**. Autonomy for mars rovers: past, present, and future.** In *Computer*: December, 2008. (pp. 44-50). *IEEE Press. (available at http://marstech.jpl.nasa.gov/publications/z02_0102.pdf)*

Databases and Websites

- NASA Home Page (http://www.nasa.gov/)
- European Space Agency Home Page (http://www.esa.int/esaCP/index.html)
- JPL/CalTech "BEACON *eSpace*" database (http://trs-new.jpl.nasa.gov/dspace/)
- NASA Technical Reports Server (http://ntrs.nasa.gov/search.jsp)
- JPL/CalTech PhotoJournal (http://photojournal.jpl.nasa.gov/)
- Harvard SOA/NASA Astrophysics Data System (http://adsabs.harvard.edu/index.html)
  - SOA/NASA Wunderlich "Library" (http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=wunderlich&libid=4a0f09cf26l)
- National Geographic Archive (http://ngm.nationalgeographic.com/archives)

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J. Wunderlich Vocabolario Italiano

Non parlo L'Italiano molto bene, ma sto imparando

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POST-COURSE REFLECTION

Before teaching the course I flew into Zurich on June 18th, 2009 and stayed in Winterthur, Switzerland. I then drove approximately 10 hours through the Swiss and Italian Alps to get to Trento. I stopped in Samedan, Switzerland and Oberbozen, Italy. On the way back to Zurich I only needed to drive six hours via the Autostrada through Austria; I stopped in Bludenz, Austria.

I successfully taught the course over a two week period to eight Engineering Ph.D. students, two Engineering faculty members, and two full-time researchers. Here is a picture of five of the most dedicated Engineering Ph.D. students (and good friends!):

Future variations of this course will involve customizing course content to specific research of the students in the course; this will include developing detailed lectures on current related research, followed by lecturing on possible ideas for future research. Also, my advice to anyone planning a trip to Italy is to fly as directly as possible to a city in Italy, then travel by train within Italy; i.e., my 10-hour experience of driving over the Alps from Zurich was not an optimal path – and my most beautiful views of the Alps were actually in Trento and in Oberbozen, one hour north of Trento (next to Bolzano, Italy).

Acknowledgements:
Thanks to the DIMS department for your generosity, including the beautiful accommodations at the Appartamento alla Finestra sull'Adige. Special thanks to Dr. Mario De Cecco for the many communications needed to make this trip possible, for your excellent feedback regarding the course, for the special attention you gave me while in Trento, for your great meals and cooking tips, and for your very generous offers to visit your wife and mother while I was in Italy. Also, thank you everyone for the many dinners and great conversations we enjoyed together. Ci vediamo presto . . . spero!