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Updated 1/25/2018

(1/16/2018)

ENG ME/SE 740

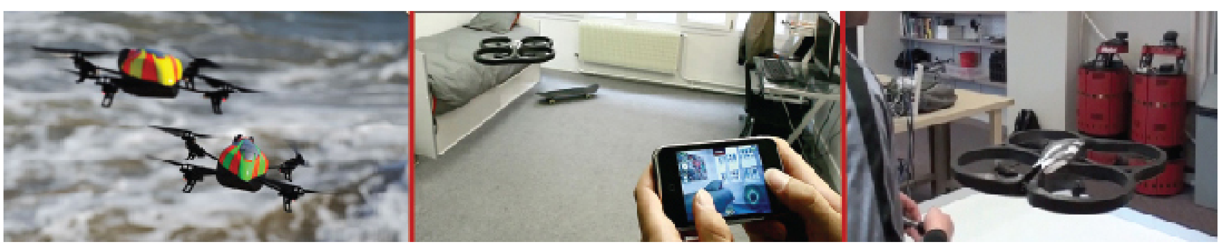
TERM PROJECTS IN INTELLIGENT MECHATRONICS

Some of these projects have been done before; some have never been done. They are offered only as ideas to guide your thinking as you come up with your own project proposal.

I. Lab Oriented Projects:

1. New Concepts in User Interfaces for Controlling Intelligent Machines. The Apple iPad™ was introduced in mid 2010, and at this writing, nearly two hundred million have been sold. Mobile devices like smart phones and tablets provide an enormous range of new opportunities for the design of user interfaces to intelligent machines. Projects that explore various aspects of these opportunities include

A: *Implementing a user interface that is intuitive and easy to use is challenging.* There are apps for the iPhone and iPad that provide beautifully intuitive interfaces for flying a single *Parrot AR.Drone*™ quadricoptor. For this inexpensive and high quality UAV, the challenge is met by having many parts of the flight-control system operate completely autonomously. Thus, the three degrees of freedom of pitch-roll-and yaw operate stably using control loops that are closed through a sensors and a microprocessor on board the UAV. Altitude and horizontal position are controlled automatically, and the user is only required to specify the altitude and position that are desired. A possible term project is to do an extensive literature survey of human interfaces that have been implemented on various remotely piloted vehicles. The survey should include well-known systems like the Predator and Golden Hawk as well as smaller deployed systems. How could these be improved?



B: *User interfaces for small squadrons of mobile robots or UAV's.* While the existing apps that use the iPhone and iPad to fly a single *Parrot AR.Drone* quadricoptor work very well, equivalent software that will allow a single user to control the flight of multiple UAV's remains largely undeveloped. Part of what is needed to enable such software is a conceptual framework for managing the the real-time information flow from the human operator to the machines. It would be tedious for a human operator to control every motion segment of the individual UAV's. One approach to this problem is to organize all flight regimes in terms of control hierarchies in which only one UAV that is designated *leader* is directly controlled by the human operator. The remaining UAV's will then use reactive control protocols to respond appropriately either directly to the commands that are sent from the operator to the leader or to the sensed actions of the leader. A possible term project for ME/SE 740 is to design and provide a detailed analysis of reactive protocols enabling various realistic squadron missions.

C: *Write an extension to the Parrot AR.Drone user interface.* Take the existing user interface and extend its functionality in some interesting way. Note that a project along these lines would require that you have an iPhone, iPad, etc. and that you have access to a developer's kit.

2. Experiments in Cooperative Control—The *blind robot* problem. A great deal of current research is aimed at understanding group behaviors of multiple robotic devices. This is especially interesting in the case in which groups of mobile robots with varied sensory-motor capabilities are required to play component roles in completing complex tasks. Consider, for instance, the case in which a mobile robot's sensors fail. It may still be possible for the robot to navigate in a congested work space, provided adequate communication of sensor readings from other robots and stationary beacons is available. Motion control based on such distributed sensing is challenging, however. Some of the problems that must be addressed are: (i) feedback laws must be based on asynchronous sensor data, (ii) packet losses and fading communication channels may limit performance, and (iii) there will be topological obstructions preventing the feedback laws from being globally asymptotically stabilizing. (See Baillieul, "The Geometry of Sensor Information Utilization in Nonlinear Feedback Control of Vehicle Formations," in *Cooperative Control*, Kumar, Leonard, and Morse, eds., Springer Lecture Notes in Control and Information Sciences, Vol. 309, Springer-Verlag Heidelberg Berlin, 2005.)

II. Math Oriented Projects:

3. Group Theory and Intelligent Mechatronics. At the beginning of the term, we'll see how the coordinate transformations of robotics were represented in terms of elements of $SE(3,\mathbb{R})$. $SE(3,\mathbb{R})$ is an example of a *Lie group*; this is a group on which there are defined notions of dimension and differentiation. Each of the three types of one degree-of-freedom mechanical joints (revolute, prismatic, and screw) corresponds to a type of one dimensional subgroup of $SE(3,\mathbb{R})$. Group theory has provided an enormously rich source of abstractions for robotics, computer vision, and communications theory. A possible term project would be to explore the theory of robot kinematics in terms of the structure of the various subgroups of $SE(3,\mathbb{R})$. A starting point will be our class lectures as well as the material in the text (Murray, Li, and Sastry). Research is needed to understand the use of group-theoretic methods to describe symmetries and patterns in vehicle formations. You might also want to look at the role group theory has played in modeling space-time diversity in coding for wireless communications. Are there special features of wireless communications for controlling the coordinated movements of groups of mobile robots that lend themselves to descriptions in terms of group theory?

4. Lattice Theory and Robotic Navigation through Feature Networks. Animals such as bats and birds are sufficiently agile flyers that they can move rapidly through dense forest clutter. It is of great interest to give small UAVs the same capability. A term project that could be seen as a first step toward more advanced research involves developing closed-loop obstacle-avoiding trajectory guidance that will closely mimic observed trajectories based on bat and bird flight data. For cluttered environments, an interesting research objective is to develop a theory of motion control in which physical obstacles are viewed both as obstructions that must be avoided and as waypoint beacons that can be used to guide a vehicle's transit through the obstacle field. In order to develop the theoretical foundations, clutter can be modeled as planar or spatial lattices. Points in the lattices correspond to obstacles which may also be used as waypoint beacons for localizing the UAV's position. Throughout the flight, the UAV will need to frequently switch its control laws as it leaves the proximity of one set of obstacles to enter the proximity of another set. The goal is to develop a switching protocol together with appropriate perception-based feedback laws that will allow the UAV to efficiently and safely transit the obstacle field. The mathematical foundations of this research will include the theory of geometrical lattices and might also include recent work on Boolean control networks: D. Cheng, "Disturbance Decoupling of Boolean Control Networks," *IEEE Trans. on Automatic Control*, 56:1, 2011, pp. 1-10. A variety of perceptual modalities involving distance sensing, optical flow sensing, and more can be considered.

5. Theory (and Possible Experimentation) of Computer Vision for Motion Control of Autonomous Robots and UAV's. Birds and flying insects are able to perform well without using predetermined waypoints or an external position reference system. To enable true autonomy, there is a need for algorithms to localize and navigate relative to landmarks or other visually distinctive features in the environment. Algorithms of this type can be enabled by spatial representations that make use of time-to-contact and topological connectivity. Building on the work documented in

`https://open.bu.edu/browse?value=Seebacher%2C+J.+Paul&type=author`

and also in

`http://people.bu.edu/johnb/Perceptual_Aliasing_Signed.pdf`,

a suitable ME/SE 740 project could be to develop enhance control and navigation algorithms for camera enabled robots and UAVs.

6. Toward a Theory of Action-Mediated Communication. The principles of information theory (See, e.g. Cover and Thomas, *Elements of Information Theory 2nd Edition*, Wiley-Interscience; 2 edition (July 18, 2006), ISBN-10: 0471241954, ISBN-13: 978-0471241959, 776 pages.) dictate that when messages are encoded for transmission through a communication channel, symbols in a code book should be assigned to a message source in such a way that frequently occurring codewords are the shortest (require the fewest bit to express) while infrequently occurring codewords are allowed to be longer. We would like to establish a similar guiding principle for "action-mediated" communication. When the motion of a physical system is used to encode a message, there is typically an associated cost that is of interest—e.g. the energy required to produce the motion, the spatial extent of the motion, or the time that is needed to execute the motion. Thus, in using the motions of a controlled dynamical system for the purpose of communication, we will want to encode messages in such a way that the least costly motions are the ones used with the greatest frequency.

Framed in this way, the problem of optimal action-mediated communication shares common features with the *standard parts problem*, where the goal is to assemble a number (say n) of objects using an inventory of m different kinds of parts in such way that over time the averaged cost of assembling the objects is minimized. A possible term project is to explore this circle of ideas for action mediated control in the context of applications to team sport play (How do team members efficiently communicate with each other by means of the way they move on the playing field?), to dance (How do dance partners communicate with each other to chose sequences of moves that will be judged to be appealing while at the same time making maximally modest demands on the energy reserves of the dancers?), and to problems in synthetic biology where there is now interest in establishing registries of standard biological components for the synthesis of novel biological systems. References that also mention possible applications to quantum information processing include:

W. S. Wong and J. Baillieul, "Control Communication Complexity of Nonlinear Systems," *Communications in Information and Systems*, 9:1, pp. 103-140, 2009. http://people.bu.edu/johnb/CIS-9-1-A5-wong.pdf

J. Baillieul and W.-S. Wong, "The Standard Parts Problem and the Complexity of Control Communication," in *Proceedings of the 48-th IEEE Conf. on Decision and Control*, Shanghai, China, December 16-18, 2009, pp. 2723 - 2728. Digital Object Identifier: 10.1109/CDC.2009.5400

7. Nonholonomic Path Planning. Certain mechanical systems move under the influence of velocity constraints which cannot be derived from pure position constraints. (Think of the motion of an ice-skate, which can only move in a direction aligned with the blade of the skate.) Such constraints are called *nonholonomic*. Study and write a paper on motion planning for robotic devices (wheeled robots, multifingered hands grasping smooth objects, etc.) whose motions are governed by nonholonomic constraints. Special cases of current research interest involve motion planning for robots carrying dynamic loads and motion planning for groups (formations) of mobile robots. There are several largely unexplored research directions related to path planning for groups of autonomous mobile agents:

- **Accounting for dynamic constraints.** Even in the case of a single robot, planning trajectories which have timing requirements and which take account of dynamic constraints (such as limiting the amount of energy transferred to a fluid or elastic load) can be quite challenging. For groups of two or more mobile robots, trajectory planning in the face of such dynamic constraints remains an area where fundamental research is needed.
- **Accounting for intermittency in sensing and communication.** You can develop ideas, models, and simulations of multiple robot agents which are cooperatively engaged in group activities (e.g. moving through a space with obstacles) where all sensing and inter-agent communication is subject to uncertainty and intermittent disruption.
- **Efficient and reliable movement using an inventory of standard motions.** One way to deal with such intermittency is to use open-loop motions during intervals in which sensor readings and communication updates are not available. Using ideas from the *standard parts problem* mentioned above, develop a theory of standard motions for simple nonholonomic vehicles. The goal is to have an inventory of standard motions that is sufficiently rich that a vehicle can achieve a reasonable set of motion objectives by means of concatenating standard motions. The set should also be chosen so that an efficiency criterion in terms of a reasonable control metric is met.

III. Soft Robotics:

8. Studies in Synthetic Psychology In previous classes, there has been a great deal of interest in group behaviors of different types of "Braitenberg's Vehicles." As you recall, the simple "vehicles" described in *Vehicles* by Valentino Braitenberg (MIT Press, 1984) move according to simple kinematic laws determined by primitive neural responses to information from simple sensors. These neural responses are determined by simple "wiring" schemes, and while Braitenberg's original treatment of synthetic neural architectures was primarily analytical, many people have developed extensive simulation tools which support computer-based studies of fairly complex "vehicles" and their motions.

9. Studies in the Cognitive Psychology of Human/Robot Interaction and Decision-Making. The goal of the research involved in this topic is the understanding of methods to capture, model, and represent, human behavior in a variety of tasks involving collaborations with autonomous robots. Models of cognitive and social psychology will inform the work. A particular objective is to develop a fundamental understanding of how humans and autonomous machines can operate together to efficiently accomplish common goals. A number of specific questions can be posed and studied: There will clearly be some tasks in which humans are likely to either perform below their potential or even to make mistakes in cognition or judgment due to workload, fatigue, preconceived notions, incomplete information, inability to process available data, inattention, and boredom. Research is needed to define laboratory situations in which it is possible to study how robots might help humans to perform better in situations where such factors lead to degraded performance in making decisions. Another interesting set of questions can be asked regarding how human behavior differs from ideal decision makers in particular problem domains and whether decision aids can be designed to help people make better decisions.

Finally, there are many open questions regarding the potential of mixed teams of humans and robotic agents. The past decade has seen substantial progress in moving from direct operator control to supervisory control of autonomous systems. A primary goal of these past efforts has been to reduce the number of humans and/or the level of skill and training required to effectively manage a certain number of autonomous systems in various mission settings. Research is needed to understand how a mixed human/robotic team can operate more capably than a purely human one.

10. Dextrous Robotic Devices Made from Soft Materials. Laproscopic procedures have had a transformative effect for a number of common surgical interventions—resulting in shorter hospital stays, faster recovery, and less post-operative pain for most patients. Despite notable successes in a variety of treatments, many surgeries cannot be performed laproscopically because the surgery sites cannot be reached with the existing instruments. One of the great engineering challenges is to increase the flexibility and articulation of surgical instruments so that they can be used effectively and safely in and around the soft tissues of organs in the body. The current state-of-the-art is the Flex^{TM} systems from Medrobotics: `https://www.youtube.com/watch?v=nl2LnvyYNAI`. A suggested term project which can be completed within the time and available resources is the design and fabrication of simple prototype devices that are made from soft but controllable materials. A first step on this project could be the replication of the finger-like device described in `https://www.youtube.com/watch?v=gPYjo-W2ctU`. Only slightly more complex is the McKibben artificial muscle element described in `http://youtu.be/sAHNJdxF6Cw`. The ultimate aim of compliant device designs is to create soft robot limbs that can slide through small apertures, move independently, and bind together to form wireframe structures with complex topologies that can be used to perform a variety of surgically relevant manipulations.

IV. *Mechano-informatics* - The Interplay of Physics, Communication and Information Theory:

11. Problems in Communications and Information Processing in the Design and Implementation of Feedback Control. Study the effect of *latency* and other aspects of communications overhead in *Bluetooth*^{TM} and other wireless communications technologies. Take a benchmark undergraduate control-laboratory project such as stabilizing an inverted pendulum. For what parameter ranges (parameters being mass, inertia, and so forth) can we close feedback loops through *Bluetooth*^{TM}, *ZigBee* and other low power, low bandwidth channels? How do data requirements depend in general on control system parameters?

12. Vison-Based Search and Surveillance Missions. There is now a fairly mature body of literature concerned with the problem of placing guards in an art gallery such that every point in the gallery is visible to at least one guard. (See, e.g. [1].) Under the assumption that the space in the gallery, its contents, and visual obstructions are rectangular polygons, upper bounds on the number of required stationary guards are given in terms of the total number of vertices of these polygons. This problem can be shown to be equivalent to finding a minimal covering of the gallery space by a set of star shaped polygonal regions.

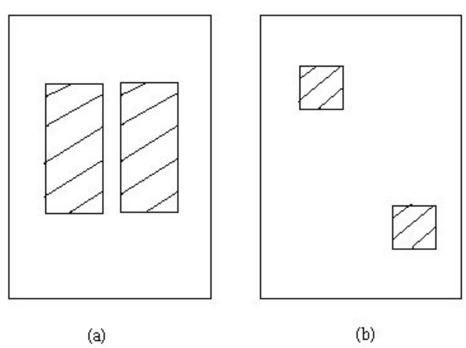


Figure: In the polygonal idealization of the art gallery problem, guards must must be able to observe all of of a not necessarily simply connected space bounded by the sides of polygons. In this figure, we consider only rectangular polygons.

This project calls for research on a class of related problems which we refer to collectively as the mobile museum guard problem. The simplest of these problems is to find the shortest path a mobile guard can follow to inspect or observe the entire space.

REFERENCES:

1. J. O'Rourke. *Art Gallery Theorems and Algorithms*, Oxford University Press, 1987.

2. J. Grace and J. Baillieul, "Stochastic Strategies for Autonomous Robotic Surveillance," Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference, Seville, Spain, December 12-15, 2005, pp. 2200-2205. Digital Object Identifier : 10.1109/CDC.2005.1582488

3. J. Grace and J. Baillieul. "The Fastest Random Search of a Class of Building Interiors," In *Proceedings of the 17-th International Symposium on Mathematical Theory of Networks and Systems*, Kyoto, Japan, July 24-28, 2006, pp. 2222-2226.

13. The Smart Grid—Challenges and Opportunities. A great challenge for the United States in the years ahead will be ensuring adequate electric energy. New sources are badly needed, and there is a growing sense that more efficiency in the use of existing sources is needed as well. Some of the new sources may be renewables such as solar, wind, and others. Part of the challenge in making use of these sources of electric power is the associated intermittency. Current thinking is that this intermittency can be dealt with by having a broad mix of different electric energy sources—from coal, to natural gas, and nuclear. The effective use of real-time information in the operation of the electric power grid is an important topic for research that can be started as a term project. Some specific possibilities include:

A: *Build a small-scale model of an electric energy grid in which there is a realistic mix of generation sources.* Use your model to find optimal ways in which to use renewables like wind and solar. Can new classes of energy use help? For instance, it may be possible to use intermittent sources for charging batteries in things like plug-in electric vehicles.

B: *How much can more widespread adoption of advanced power electronics help in the incorporation of renewables into the generation mix?* Advanced photovoltaic (PV) systems use power conditioning circuits to convert DC current to grid-acceptable AC. Such circuits can also be used to improve grid operation during times of stress.

C: *What is the role of new energy markets?* Explore what can be accomplished by having individual commercial buildings buy and sell energy and capacity reserves. What is needed in terms of real time information including marginal costs, line losses?

D: *What can be achieved using micro-grids and information systems for controlling and coordinating smart appliances*? A great challenge for grid operators in times of high demand is that random fluctuations in the intermittent demand of appliances like air conditioners and water heaters can occasionally lead to large and hard-to-predict loads increase stress on the network at the least favorable times. If individual appliances can sense the state of the grid, they can be programmed to adjust their demands for power in order to enhance the security and overall performance of the grid. A term project that investigates the risks (costs) associated with randomly occurring large peak loads associated with appliances that are not grid-aware may reveal important benefits to be derived from micro-scheduling the operation of selected classes of appliances.

14. Research to understand the INFOMAX principle for robotic networks. Research is needed to understand general principles of how the placement of nodes in a network and the interconnections between the nodes should be arranged so as to maximize various network-specific measures of information that is collectively acquired and held by the nodes. A prototypical class of problems involves models of perception, communication and information flow between pairs of networks. A key feature in such models will be abstracted descriptions of information sources that capture common features of data from (i) spatially-distributed sensor networks, (ii) neural impulses passing among regions of the brain, and (iii) salient features of continuum data in spatially varying random fields. The fundamental problem of information flow between a source and a receptor network (e.g., a data-collecting sensor/robotic network in the case of (i) and (iii) above, and selected cortical brain regions in the case of (ii)) is to understand how the receptor network receives the maximum information available in the source networksubject to operating constraints such as noise, signal-to-interference ratios, energy requirements

(See Berger, 2003.) and other data-rate limiting factors. The objective of the research may be phrased as the problem of finding mechanisms that implement the *infomax* principle as proposed in the classic paper by Linsker (1988).

REFERENCES:

1. R. Linsker. "Self-organization in a perceptual network." *IEEE Computer*, 21(3):105317, 1988.

2. T. Berger. "Living Information Theory: The 2002 Shannon Lecture." *The IEEE Information Theory Newsletter*, 53:119, 2003.

15. Data, Software, and Mathematical Foundations of Machine Learning and AI. One hundred percent of our incoming class of PhD students in Systems Engineering this year reported that their main research interest was machine learning. Some historians trace the origins of machine learning to the eighteenth century when the Reverend Thomas Bayes wrote an essay entitled "An Essay towards solving a Problem in the Doctrine of Chances." Most people—with due respect for Bayes—would probably date the real beginnings of machine learning to the early 1940s and 50s when work of Alan Turing and Marvin Minsky was first published-accompanied by the invention of digital computers (ENIAC, Manchester Mark I, etc.). Since its introduction, machine learning has been viewed as a potentially important enabler of robotics, but it is fair to say that it has not yet realized this potential. Several things could now change this.

As the processing capability of computers has increased exponentially for decades (in accordance with Moore's law), radically new concepts in distributed (cloud) computing have created the Internet—a distributed digital knowledge base that could not have been imagined in 1993, the launch year of the World Wide Web. There has been an explosive proliferation of digitally archived data — both proprietary and public. A few of the ever increasing numbers of examples of publicly accessible data sets are

(a) The CIFAR-10 dataset consisting of 60,000 32×32 color images of 10 classes of objects, with 6000 images per class, [4],

(b) 150 Mbytes of flight trajectories of *Myotis velifer* bats reconstructed from 15 Tbytes of video recordings of emergences from the Bamberger cave in Texas. (Data in [2], analysis in [1].), and

(c) The 2010-2013 New York City Taxi Data, curated by Dan Work, [3], comes with the caveat that "All . . . obvious trip errors should be discarded in any analysis. In our preliminary investigations, these errors account for roughly 7.5% of all trips."

A few hours of web searching will yield many other interesting data sets. Large publicly accessible data sets are proliferating both because data is increasingly easy to archive and also because funding agencies are now requiring data to be included as one of the reported products of sponsored projects. (See, for instance, `https://www.nsf.gov/pubs/policydocs/pappguide/nsf15001/gpg_2.jsp#IIC2j` .)

Given this background, it is not surprising that current research in systems engineering and computer science is focused on AI in general and machine learning in particular. Some specific examples:

(*i*) Within the broad disciplinary domain of systems and control, the field of systems identification provides techniques for deriving mathematical models of dynamical systems based on input-output data. The most mature aspects of systems identification deal with time-invariant linear systems in which there is a convolution operator relating the input and the system's output. The problem of sysID is to find the impulse response from observed data. Such deconvolution problems appear in many fields including biology, computer science (computer vision) physics, and engineering. While many aspects have been refined to provide a corpus of software in the Systems Identification Toolbox in Matlab^{TM} [8], recent research has sought to make improvements through connections with machine learning techniques that have been developed independently and are focused on reproducing kernel Hilbert spaces. This research has been illuminated, among a number of ways, by applications to robot motion control, [5].

(*ii*) With the appearance of new cloud resources and many publicly available data sets, there has been renewed interest in neural networks as a means to recognize features in images,[4], to do so-called deep learning, [6], and to provide the basis of machine learning of languages, [7].

Term project ideas: What kernel methods, classical linear systems ID, and neural networks have in common is the "training" of models from data. Taking the very broad view that training simply means assimilating information, an interesting class of problems related to the methods described as well as to many more is how should we value information in terms of its usefulness in training. Some specific research questions are:

1. Which learning tasks are difficult and which are easy? For instance, research in image and video processing sometimes focuses on anomaly detection. For the data set [4], one might be interested in using the training set to develop a computer program that would simply recognize whether a test image belonged to one of the ten classes in the data. Can this anomaly detection problem be solved more easily than the image recognition problem? A similar problem can be posed for the system identification methods: specifically, are there comparatively easy systems in terms of how large training sets need to be? Complexity measures such as the *Akaike information criterion* (AIC) may play a role.

2. A related question is whether there are information-based techniques that will enable methods of improving training sets - both by adding information rich examples as well as by culling and discarding elements of the training set that have little or no training value? Can networks be more efficiently trained with smaller but "better" training sets? Are there useful information-theoretic measures of the training value of data—images in particular, say?

3. A meta-question regarding software and data is how does published STM research of 2016 differ from research published in 1986? This topic is comparatively "applied" in nature, and can be formulated precisely as follows. Take the top 20 (most highly cited) journals published by the IEEE. (I can give you the list.) Go through all the main articles published in 1986 and count the references to data sets as well as algorithms and computer code that are cited. Compare this with similar counts for 2016. Are data and computer code more prevalent in today's research than 30 years ago? Whether the answer is yes or no, it will be of interest either way.

REFERENCES:

[1] Zhaodan Kong, Nathan Fuller, Shuai Wang, Kayhan Özcimder, Erin Gillam, Diane Theriault, Margrit Betke, and John Baillieul, ' "Perceptual Modalities Guiding Bat Flight in a Native Habitat," *Scientific Reports - Nature*, **6**, Article number: 27252 (2016). http://www.nature.com/articles/srep27252.

[2] Flight data for cave emergence of Myotis velifer, July, 2013. John Baillieul, Curator.
http://www.baillieul.org/data/CSV/

[3] 2010-2013 New York City Taxi Data, Dan Work, Curator.
https://publish.illinois.edu/dbwork/open-data/

[4] https://www.cs.toronto.edu/∼kriz/cifar.html

[5] Gianluigi Pillonettoa, Francesco Dinuzzob, Tianshi Chenc, Giuseppe De Nicolao, and Lennart Ljung, "Kernel methods in system identification, machine learning and function estimation: A survey," *Automatica*, Volume 50, Issue 3, March 2014, Pages 657 - 682.

[6] http://caffe.berkeleyvision.org/

[7] Gideon Lewis-Krause, "The Great AI Awakening," *New York Times Magazine*, Dec. 14, 2016.

[8] https://www.mathworks.com/help/ident/

Due dates for term project elements.

1. Project proposals (one page) due 2/06/18.
2. Interim progress presentation due around 3/15/18. This will involve a formal class presentation in which you present

- Why you chose this project and why it is important and interesting. (These questions should, of course, be addressed in your project proposal as well.)
- What is the relevant background? If it is original research, what is the state of the art, and what do you hope to accomplish? If it is some type of hardware or software design, what are the main challenges going to be?
- How has the definition or scope of you project changed in the four weeks since you submitted your project proposal?

3. Final project class presentations will be in late April. Final project reports will be due on May 1.