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ENG ME/SE 740

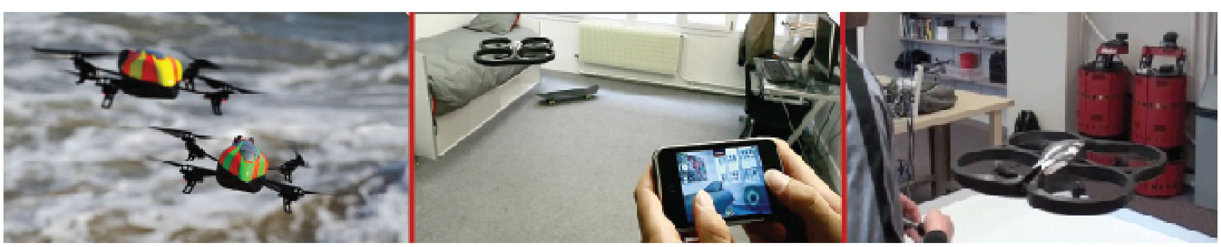
PROTOTYPE TERM PROJECTS IN INTELLIGENT MECHATRONICS

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. Human-Robot Interface Projects:

1. New Concepts in User Interfaces for Controlling Intelligent Machines. The Apple iPad$^{\text{TM}}$ was introduced in mid 2010, and at this writing, nearly four 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*$^{\text{TM}}$ 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 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 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. For a computer scientist's perspective on "reactive control," see "Technical Perspective on "Reactive Control of Autonomous Drones"," *Communications of the ACM*, V. 61:10, October 2018 p. 95, DOI:10.1145/3264411.

C: *Write an extension to the Parrot AR.Drone user interface.* Take the existing user interface and extend its functionality to allow the user to control a fleet of robots. Note that a project along these lines would require that you have access to a device that will serve as your command interface—such as an iPhone, iPad, etc.

2. 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.

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 recommended course texts (Murray, Li, and Sastry and Lynch and Park). Research is needed to understand the use of group-theoretic methods to describe symmetries and patterns in vehicle formations. Lie group theory has also been applied in structural mechanics in recent work on the control of deformable structures. This work has reformulated Cosserat rod theory in the language of Lie groups—most specifically SE(3,$\mathbb{R}$). The so-called geometrically exact models of rods (such as Cosserat rods) treat rods as slender (one-dimensional) structures specific sets of permissible strains—typically bending, torsion, shear, and extension. How would such strains be characterized in terms of SE(3,$\mathbb{R}$) and its lattice of subgroup types? Background reading for this topic should include S. Grazioso, G. Di Gironimo, and B. Siciliano, "A geometrically exact model for soft continuum robots: The finite element deformation space formulation," *Soft Robotics*, 2018. [Online]. Available: https://doi.org/10.1089/soro.2018.0047.

The class lectures will focus on representations of SE(3,$\mathbb{R}$) and its subgroups according to standard approaches using 4×4 matrices, but a highly inventive previous term project developed an alternative approach to representations based of a specific application to protein docking. This work was published in P. Vakili, H. Mirzaei, S.

Zarbafian, I. C. Paschalidis, D. Kozakov and S. Vajda, "Optimization on the space of rigid and flexible motions: An alternative manifold optimization approach," 53rd *IEEE Conference on Decision and Control*, Los Angeles, CA, 2014, pp. 5825-5830. doi: 10.1109/CDC.2014.7040301. Mathematical explorations along these lines make great term projects.

4. 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 below in Paragraph 10), 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. Computer Science Meets Control Theory

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://hdl.handle.net/2144/15191`,

and also in

`https://hdl.handle.net/2144/27453`,

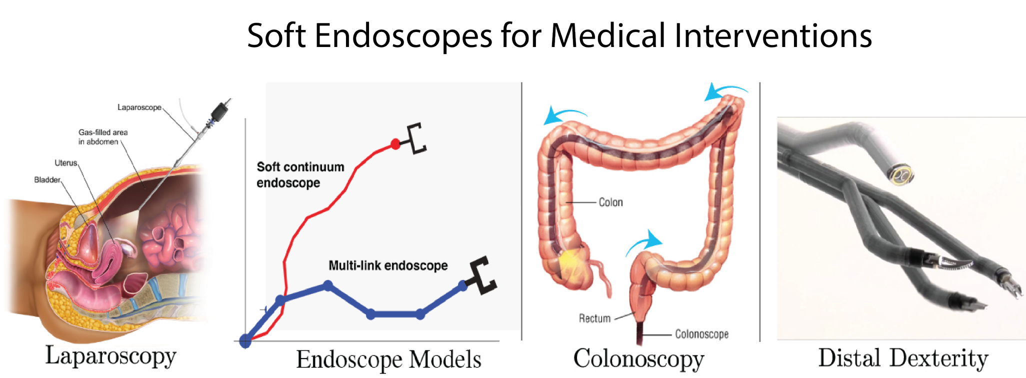
a suitable ME/SE 740 project could be to develop enhance control and navigation algorithms for camera enabled robots and UAVs.

6 Neuro-Inspired Perception and Navigation. This is a project that is related to the previous paragraph. Important research remains to be done in order to understand how movement can be guided by visual perception. It is critical to realize that when moving, where we are and what is around us is not sufficient to guide navigation; we also need to know where we are coming from, i.e., account for "differences" between consecutive scenes. The goal is to develop new principles of motion control in which control signals are synthesized from very large sets of rapidly evolving input data (neurons firing in the visual cortex) and whose individual elements are too ephemeral and noisy to be useful but which turn out to be meaningful in the aggregate.

7. Cloud Based Robotics—Robot projects using AWS *RoboMaker.* New since last year's version of this list of term project prototypes, Amazon Web Services (AWS) has released a cloud-based service called RoboMaker, https://aws.amazon.com/robomaker/. This provides a robotics development environment for application development, robotic simulation, and a robotics fleet management service that can be customized for deployment, update, and management of a user's fleet of robots. Leveraging the capabilities of ROS (the robot Operating System) and Gazebo (simulator of mobile robots or groups of mobile robots) RoboMaker provides a simulation environment in which robot control code can be developed, tested, and actually deployed on a real robot. Robotics is one of several technologies in which Amazon is supporting developers at a variety of scales and price points. Deploying a simulated fleet of robots for applications such as search and surveillance, warehouse fulfillment, or autonomous vehicle operation would be a term project with the potential of breaking important new ground for future offerings of the course. The project will also be an opportunity to gain experience with ROS, Gazebo, and AWS Cloud9. This project will be graded on the basis of creativity and the sophistication of the simulation.

IV. Soft Robotics:

8. Dextrous Robotic Devices Made from Soft Materials (a). 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. A potentially impactful project would be designing a slender body mechanism with a centimeter-scale diameter and soft fluidic actuators inspired by the muscular hydrostat structure found in animal limbs like octopus arms. To obtain the necessary degrees-of-freedom, the actuators will need to be arranged in longitudinal and helical directions. The device should be passively squeezable in the radial direction, while pressurization of diagonal and longitudinal actuators will govern the roll and bending degrees of freedom in addition to modulating longitudinal stiffness. Simultaneous actuation (i.e., antagonistic contraction) can enable stiffness control, and dextrous kinematics, but the challenge is to find a design that has enough control channels (e.g., flexible tubes) to bring pressurized fluid to inflatable chambers that will actuate the movement. (See also Paragraph 12 below.)



9. Dextrous Robotic Devices Made from Soft Materials (b). Buckling of slender rods under various types of loading has been studied for centuries. Recently, researchers have become interested in buckling phenomena in structures that are embedded in materials other than air or water. (See, e.g., A. R. Mojdehi, B. Tavakol, W. Royston, D. A. Dillard, and D. P. Holmes, "Buckling of elastic beams embedded in granular media," *Extreme Mechanics Letters*, vol. 9, pp. 237–244, 2016.) New theories and models of buckling are essential to understanding how to control soft endoscopes inside the lumen of an organ in a living animal. Using appropriate models of soft endoscopes, perhaps along the lines of Grazioso et al. as referenced in Paragraph 3 above, develop models of buckling in the presence of physical constraints as would be encountered with the endoscope is enclosed within the lumen of an intestine.

V. *Mechano-informatics* - The Interplay of Physics, Information Theory, and AI

10. 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

11. Communication Constrained Control (a). As machines and devices of all kinds have become increasingly autonomous, there has been a corresponding interest in having the devices interoperate so as to work together on shared tasks. Networked operation of cooperating devices is key to modern transportation technologies from flight control systems on aircraft to the interconnected control processors that coordinate steering, braking, and power train functions. In many cases, actuators, sensors, and microprocessors are connected by wires, but there is increasing interest in having them communicate wirelessly. The rates at which networked devices can communicate with each other is thus limited, and such data rate constraints in turn constrain the performance of the system. With networks of sensors, actuators and processors in mind in say late model automobiles, a possible term project could examine current wireless networking technologies like *Bluetooth*^{TM} and *ZigBee* and estimate performance limitations that can arise due to noise, packet loss, and the degree of asynchronism in the operation of nodal components of the network.

12. Communication Constrained Control (b). Device arrays of MEMS actuators such as micro-pistons and micro-valves have moved beyond the "proof-of- concept" stage in which relatively small arrays, with between four and twenty actuators on a single chip, to designs with hundreds or thousand devices are packed onto a single chip. In such device arrays, it is necessary to close feedback control loops using communication channels shared by multiple device elements. Work is only just now beginning on the switching and encoding strategies that will be needed to produce stable closed-loop dynamics across a broad spectrum of applications. We are finding that many of the bandwidth assignment issues that are predominant in managing the traffic in modern communications networks are also present in some form in networked actuator arrays with the additional challenge of needing to deal with severely fast time constants. This project is to develop the elements of control and communications theory needed to assign channels and effectively encode and transmit actuator and sensor data over the links in a device network. Issues of multiplexing, addressing, and resource allocation will need to be addressed.

A similar set of challenges arises in controlling the soft endoscopes mentioned above in Paragraph 8. For interaction with living tissue, soft robots typically utilize fluidic actuation in which fluids like water, air or other non-toxic gases are used to inflate bladders to move and/or stiffen the devices. A project of considerable interest and importance would be to design devices and fluidic actuation schemes that possess enough degrees of freedom to perform delicate maneuvers inside an animal body cavity or lumen. Novel sensing concepts are required, but an even more fundamental question is how to distribute enough fluid lines within the small dimensions of the device to enable the required degrees of freedom. What are performance metrics that will be relevant to the operation of such devices? Can you mathematically characterize dexterity and perhaps uncertainty in terms of something like the *manipulability index* that has been defined for rigid robots?

13. 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 network subject 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):105-317, 1988.

2. T. Berger. "Living Information Theory: The 2002 Shannon Lecture." *The IEEE Information Theory Newsletter*, 53:1-19, 2003.

14. 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 projects in machine learning and AI: 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. Are there 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?

2. Regarding the soft-robot applications described in Paragraphs 8, 9, a major challenge is to instill in the robot the ability to feel its environment. An ambitious project for the course will be to design a means of sensing deformations that can be coupled to learning techniques to have the robot recognize textures and shapes of objects within certain prescribed classes—e.g., bricks, balloons, and simulated or real animal tissue.

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 2/05/19.
2. Interim progress presentation due around 3/14/19. 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. Written project reports will be due on May 2.