Personal Statement - Prof Thomas Bewley - UCSD Flow Control & Coordinated Robotics Labs

In the last few years, my team has continued to evolve our research, service, and teaching portfolios. On behalf of myself and my lab, I would like to briefly survey some of our newest directions in all three of these areas here, with links to some of our key recent results. I also refer the reader to my Personal Statement from 2020, to survey some of my other activities (many of which are still ongoing) since COVID, including substantial refinements to the Renaissance Robotics (http://robotics.ucsd.edu/RR.pdf) and Numerical Renaissance (http://robotics.ucsd.edu/NR.pdf) texts, and the Renaissance Repository (https://github.com/tbewley/RR) of corresponding pedagogical codes.

New directions in our research portfolio:

1. *Reversible random number generation* [http://robotics.ucsd.edu/ReversibleRNG.pdf - submitted]

   represents original (CS-focused) sole-author work in a field that I have never published in. I believe I have digested this field well enough to now contribute significantly to it. The research need that motivated my study of this problem is the variational (adjoint-based) analysis and optimization (of various control, identification, and estimation parameters) in Monte Carlo simulations, Ensemble Kalman Filters, and Particle Filters, in which statistically-good PRNGs are essential for generating appropriately-perturbed trajectories in forward-in-time simulations, and inexpensive exact reproduction of the random excitations perturbing these trajectories in their retrospective (backward-in-time) analysis is required. The reverse of modern, fast, statistically-excellent PRNGs didn't previously exist, so I developed them (cf. Figures 2 and 3 of this paper).

2. *A new method for approximating proportional representation in multi-seat elections based on range or approval voting* [http://robotics.ucsd.edu/pubs/BL_TRV.pdf - submitted]

   is some of my most original first-author work. It is also in a field that I have never published in, but I believe I have digested this field well enough to now contribute significantly to it as well. My various unique perspectives on game theory and noncooperative optimization motivated my new insights on this problem. An old version of this manuscript was rejected for publication a few years ago; with some new inspirations, I picked it up again last year, substantially improved it, and resubmitted. For the purpose of election reform, the new voting systems proposed, TRV/TAV, are objectively better than the well-known STV/IRV/RCV: the first selected candidate is Condorcet/IIA, and the remaining provide a *quantifiably* proportional representation of underrepresented minority interests. Also, TAV ballots are *simpler*, and TRV ballots are *more expressive*, than STV ballots.

3. *A new class of stable, spring-loaded, planar, roll-controlled, highly maneuverable robots for interior exploration of networks of pipes and ducts* [draft available, using password password checkers123, at http://robotics.ucsd.edu/UC_San_Diego_Patent_Case_SD2023-185.pdf; under review at patent office]

   is a PCT (that is, *international*) patent application (a first for our lab!) that UCSD submitted on our behalf. The need for this invention arose because we got funded by the US Army Corps of Engineers' ERDC Construction Engineering Research Laboratory (CERL), via a subcontract through GTI Energy (GTIe), to further develop a terrible idea explored at GTIe: the stabilization of two-wheeled, unstable robots, similar to MiPs (a problem for which I have some expertise), for the interior inspection of inaccessible networks of underground pipes. After studying this problem for 3 months in fall 2022, it became clear to me that the deployment of a non-robust, unstable robot design within inaccessible underground pipe networks is ill advised indeed, and the situation necessitated the development of a much simpler, stable, highly maneuverable robot design for this class of problems, which we delivered in spades (see above patent application - this is in fact the first time I have written a patent application, including claims, completely from scratch myself). With ERDC/CERL and GTIe's permission, we pivoted somewhat on the project (away from unstable robots), and are now prototyping/refining this revolutionary new design, as discussed in

   Design and characterization of torsion spring-motor integrated Series Elastic Actuators [http://robotics.ucsd.edu/pubs/jhwtb24.pdf - Published in the *2024 ICCR Proceedings*], and

   A new robot design for the interior exploration and inspection of pipe networks [http://robotics.ucsd.edu/pubs/JWB_piperobots.pdf - *Science Robotics*, submitted], and

   A miniature robot designed for internal inspection of 2-inch ID pipes with elbows [http://robotics.ucsd.edu/pubs/WJB_2in_pipe.pdf - *2025 IROS*, submitted]

   Belted Pipe Robot: A robot for internal inspection of 2-inch pipes [http://robotics.ucsd.edu/pubs/ncwb_belted_robot.pdf - 2025 *ICRA*, submitted].

Work continues; three additional papers related to this problem are currently under development:
• navigation and coordinated maneuvering with such robots using computer vision,
• localization and mapping with such robots using Kalman filtering/smoothing, and
• graph theory & path planning for efficient inspection of pipe networks with such robots.

4. State estimation of chaotic trajectories: a higher-dimensional, grid-based, Bayesian approach to uncertainty propagation, [http://robotics.ucsd.edu/pubs/hrb24.pdf, *2024 AIAA/AAS Space Flight Mechanics Meeting*, AAS 24-426], and

   Non-Gaussian recursive Bayesian filtering for outer planetary orbilander navigation, [http://robotics.ucsd.edu/pubs/hrbe25.pdf, *2025 AIAA/AAS Space Flight Mechanics Meeting*, AAS 25-194]

   are our two most recent published papers in the general area of Grid-based Bayesian Estimation Exploiting Sparsity (GBEES), a framework that I introduced in 2012 for non-Gaussian estimation of 3-*state* nonlinear chaotic systems. This framework necessitated solving the 3-*dimensional* Fokker-Planck equation, restricted to a small, evolving set of "active cells" defined on a Cartesian grid to estimate the evolution of a non-Gaussian probability distribution. At the time of its development, it was computationally intractable to extend this framework to the non-Gaussian estimation of 6-state nonlinear chaotic systems, such as those governing the evolution of the position and velocity of objects in space, which was my ultimate interest. In the time since, GPU-based computing has significantly changed what is computationally tractable, at least on certain classes of problems that parallelize well. Working together with GPU researchers in León, Spain, we have successfully and efficiently extended my "legacy" 2012 GBEES framework to problems with 4 to 6 states (that is, solving *4-dimensional to 6-dimensional Fokker-Planck equations*, restricted to small, evolving sets of "active cells" defined on a Cartesian grid), as described here:

   GBEES-GPU: An efficient parallel GPU algorithm for high-dimensional nonlinear uncertainty propagation [http://robotics.ucsd.edu/pubs/HRGB_GBEES_CUDA.pdf, *Computer Physics Communications*, submitted].

   A large number of additional papers are facilitated by this new capability, of remarkably accurate non-Gaussian estimation of 6-state nonlinear chaotic systems, both in cislunar orbit (near the Earth & Moon), and near the outer celestial bodies (near Saturn & Enceladus, as discussed in the AAS 25-194 paper above, near Jupiter, Europa, & Ganymede, etc.). Our first application-focused paper leveraging this remarkable new tool, currently under development, will study a parallel grid-based approach to the optical estimation of the mean motion of IBEX-like lunar synchronous orbiters.

5. *An extensible framework for probabilistic search of stochastically-moving targets characterized by generalized Gaussian distributions or experimentally-defined regions of interest* [http://robotics.ucsd.edu/pubs/HZB25.pdf, 2025 *Communications in Statistics - Theory and Methods,* https://doi.org/10.1080/03610926.2024.2439999] and

   Probabilistic search of stochastically moving targets using optimized time-periodic orbits of multiple search vehicles [http://robotics.ucsd.edu/pubs/ZB_periodic_search.pdf, submitted],

   are our two most recent papers (first is published, second is submitted) in the general area of *probabilistic search*, which is a fertile area (both scientifically, and with significant societal impact) for continued study and publication by our group. The introduction of the first paper above describes the importance of developing substantially better frameworks for searching for lost objects (stationary, or randomly moving) using unmanned vehicles. Recent searches (e.g., for the MH370 airliner that went missing on March 8, 2014, and for the downed F35 that was lost in the woods of South Carolina on Sep 17, 2023) highlight how poorly this is currently done, often resorting to simple "lawnmower trajectories" for the search vehicles, which is highly suboptimal. Much more clever alternative search trajectories are proposed and optimized in our investigations in this general area, including two manuscripts that will follow, which are still under development:

   • Probabilistic search of evasively moving targets using optimized time-periodic orbits of multiple search vehicles leveraging ideas from collaborative hunting, and

   • Non-Gaussian estimation of the chaotic motion of near-earth objects leveraging GBEES working together with probabilistic searches leveraging high-magnification earth-based telescopes.

   Note: my perspectives on area 5 matured substantially during a focused 1.5 month visit to Cambridge University during spring 2023 (Prof Ali Mashayek was my host; with his introductions, I had the opportunity to meet and brainstorm with many amazing folks at Cambridge).

6. Catenary Tether Shape Analysis for a UAV-USV Team [http://robotics.ucsd.edu/pubs/tob18.pdf 2018 *IROS*]

   Autonomous hanging tether management and experimentation for an unmanned air-surface vehicle team [http://robotics.ucsd.edu/pubs/TBB22.pdf, 2022 *Journal of Field Robotics*]

   Autonomous Hanging Tether Management and Experimentation for a UAV-USV Team: Sea Trials [http://robotics.ucsd.edu/pubs/tb23.pdf 2023 *OCEANS*]

   are three of our published papers regarding the tethered operation of connected UAV-USV teams (that is, unmanned aerial vehicles physically tethered to unmanned surface vehicles). This practical setting allows power to be generated on the deck of the USV, and transmitted over the tether to the nearby hovering UAV (quadcopter), thereby allowing the UAV to hover essentially indefinitely. Once the PhD student (K Talke) returned to the Navy, his team did trials in the Maritime and Seakeeping Basin at the Naval Surface Warfare Center in Carderock, and in the sea near Point Loma (see last link above) of the methods he developed while at UCSD, with great success.

7. Design and Parameter Optimization of a 3-PSR Parallel Mechanism for Replicating Wave and Boat Motion [http://robotics.ucsd.edu/pubs/tdsob19.pdf 2019 *ICRA*]

   Tension optimization of a 6-DOF cable-driven boat motion simulator [http://robotics.ucsd.edu/pubs/jb21.pdf, 2021 *Conference on Robotics Systems and Automation Engineering* (RSAE)]

   A Control Lyapunov Function-based Quadratic Program for a Cable-driven Boat Motion Simulator [http://robotics.ucsd.edu/pubs/jzb22.pdf 2022 *International Conference on Robotics and Automation Engineering* (ICRAE)]

   Workspace Analysis for Parameter Optimization of a Cable-driven Boat Motion Simulator [http://robotics.ucsd.edu/pubs/jb23.pdf, 2023 *International Conference on Control and Robotics* (ICCR)]

   Camera Image Based Moving Platform Rotation Estimation for Quadrotor Landing [http://robotics.ucsd.edu/pubs/jmb23.pdf, 2023 *International Conference on Control and Robotics Engineering (ICCRE)*]

   are five of our published papers in the general areas of boat motion simulation, and simple optical estimation of the boat attitude (which, at times, will be rapidly changing). Our eventual goal is the coordinated autonomous landing of UAVs on (first) a simulator of an USV deck in high sea state, and (ultimately) the autonomous landing of UAVs on *actual* USVs in high sea state, These five papers report essential steps in this direction.

8. *A novel policy for coordinating a hurricane monitoring system using a swarm of buoyancy-controlled balloons trading off communication and coverage* [http://robotics.ucsd.edu/pubs/BHBIF25.pdf, 2025 *Engineering Applications of Artificial Intelligence* **139** 109495]

   is our most recent published paper on the monitoring of hurricanes with swarms of sensor-laden balloons (which remains an overarching problem of significant scientific and application-oriented interest to me), and deals with certain new questions regarding the ad hoc IoT radio comm network that we plan between the balloons in the swarm. Perhaps the most interesting project that I am currently working on from the perspective of vehicle control in turbulent flows, is

   Emergence of a spontaneous singularity in the optimal guidance of buoyancy-controlled balloons in hurricanes with an absolute value penalty on the control [http://robotics.ucsd.edu/pubs/LB_singularity.pdf, under preparation].

   This new manuscript is specialized, but for those working in the areas of control theory and fluid mechanics, the singularity in the resulting feedback law is quite unexpected; also worth a look.

I have also been involved with a variety of other published projects in collaboration with other faculty at UCSD (specifically, recently, 1 with Prof S Herbert and 7 with Prof F Kuester) that, for space considerations, I will only briefly mention here (please open the links to the papers for details):

Constructing Control Lyapunov-Value Functions Using Hamilton-Jacobi Reachability Analysis [http://robotics.ucsd.edu/pubs/GZBH23.pdf, 2023 *IEEE Control Systems Letters*]

Rotor orientation optimization for direct 6 degree of freedom control of multirotors [http://robotics.ucsd.edu/pubs/scbk21.pdf, 2021 *IEEE Aerospace Conference*]

Decoupled translational and rotational flight control designs of canted-rotor hexacopters [http://robotics.ucsd.edu/pubs/csbk21.pdf, 2021 *AIAA Scitech*]

Monocoque multirotor airframe design with rotor orientations optimized for direct 6-dof UAV flight control [http://robotics.ucsd.edu/pubs/sctbk21.pdf, 2021 *AIAA Aviation Forum*]

Beaglerover: An open-source 3d-printable robotic platform for engineering education and research [http://robotics.ucsd.edu/pubs/beagle22.pdf, 2022 *AIAA Scitech*]

Mission-Oriented Trajectory Optimization for Search-and-Rescue Multirotor UAVs in Cluttered and GPS-Denied Environments [http://robotics.ucsd.edu/pubs/chbk22.pdf, 2022 *AIAA Aviation Forum*]

Cluster-based Dynamic Object Filtering via Egocentric Motion Detection for Building Static 3D Point Cloud Maps [http://robotics.ucsd.edu/pubs/cbk23.pdf, 2023 *IEEE International Conference on Robotic Computing* (IRC)]

QuadGlider: Towards the Design and Control of a Bio-Inspired Multi-Modal UAV with Compliant Wings [http://robotics.ucsd.edu/pubs/cpbk23.pdf, 2023 *IEEE Aerospace Conference*]

In summary, the eight distinct focus areas that form the bulk of my current research vision have been enumerated and explored on the previous pages (see also my **Bibliography**). Though the range of topics covered by this vision is indeed quite broad, significant deep contributions are being made in each one of them, including reversible PRNGs and voting theory. Some of these focus areas are more theory- and computation- focused, whereas some of them are more device-focused. Via the links to several of the published papers (and, draft yet-unpublished manuscript) provided above, in each of these eight specific areas, I have attempted to lay out our main contributions thus far, and my plan moving forward. There are a lot of papers and topics to digest here, but I hope this document helps to get a comprehensive overview, while allowing readers to dig in to those papers of their specific interest to get a closer look. I also strive to be a good neighbor, by being easy to collaborate with by other UCSD faculty on projects of joint interest; I indeed hope to do more of that in the future.

New directions in service

In addition to several standard service functions (reviewing papers, serving on various UCSD/MAE departmental committees, faculty searches, student exam committees, etc, wherever asked), I have, uniquely, committed to a year-long (AY 24-25) service commitment in the Mechanical Engineering Department (DFME) at the United States Air Force Academy (USAFA), paid for by USAFA. DFME at USAFA invited me to apply to this position, because they wanted me to help them beef up their analysis, controls, and mechatronics portfolios. I am working hard to make that happen, which means both educating USAFA cadets as well as the DFME military faculty leadership, and revamping some of their course materials from the ground up - specifically, in a junior/senior level mechatronics/autonomous systems course offered in the fall semester (see http://robotics.ucsd.edu/me396/), as well as a “First Course In Mechanical Engineering” (that is, a freshman/sophomore-level Statics course; see http://robotics.ucsd.edu/me220s/) in the spring semester.

It has thus far been an exercise that is at once interesting, challenging (from what seems like a former life, I do happen to know already how to “speak military”), and rewarding. To ensure that my impact at USAFA is long lasting, which is a genuine personal goal, I have requested (to UCSD and USAFA) that I extend my stay here (paid by USAFA) for a second year. I am committed to the USAF mission, as a peer-to-peer conflict direct with China in the not-too-distant-future is an increasing likely possibility that must be properly prepared for, and autonomous systems / collaborative combat aircraft (CCAs) will play a very significant role. At the same time, as can hopefully be seen in the portfolio outlined on the preceding pages, our research program remains active (focused on problems of relevance), broad, and (on the specific questions we have focused on) deep. Thank goodness for zoom.

New directions in, and perspectives on, the Art of Teaching and Learning

USAFA is an undergraduate teaching institution, and thus my commitment to come here for a year, in addition to hopefully giving me an opportunity to have a substantial impact on the DFME program at USAFA, is also having a substantial impact on my own perspectives on the Art of Teaching and Learning in engineering (at both the undergraduate and graduate levels). This is turning out to be a thoughtful time for me in this regard, as there are times when I see what is happening effectively at USAFA, and admire the discipline (on the side of both the instructors and the students) that it takes to make it happen the way that it does, whereas there are other times when I see more military-like "drilling" and "training" of "data" and "information" than I see a more open process of "guiding" engineers towards the "knowledge" and "understanding" that ultimately empowers them with effective tools for "creative ideation". I am trying to emphasize *analysis* and *automation of low-level computations* in my own teaching, as well as in my coaching of other USAFA faculty; in particular:

a) leveraging the 4 fundamental subspaces and the pseudoinverse to solve $A\mathbf{x} = \mathbf{b}$ completely, and
b) leveraging (that is, *using*, not writing…) standard computational tools (gaussian elimination, symbolic manipulation, essential components of LAPACK like eigenvalues and the SVD, etc) to, once they see what these tools do (see e.g., http://robotics.ucsd.edu/me220s/Ax_eq_b_flowchart.pdf) and how powerful they are, be able to use them confidently to begin to analyze and consider problems at substantially higher and higher levels. In particular:
   - Once you know arithmetic (but not before!), don't do arithmetic anymore; have a computer do it.
   - Once you know algebra (but not before!), don't do algebra anymore; have a computer do it.
   - Once you know partial fraction expansions (but not before!), don't do partial fraction expansions anymore; have a computer do it. etc…

The challenge that most students, and many instructors, don't at first see is the parenthetical phrases above. Specifically, students needs to develop a clear Understanding of problems over a range of levels before, from there forward, directing machines to do these (repetitive) tasks for them, in order:

i) to confirm that the answers produced by these machines are correct (trust, but verify), and
ii) to know how and why such algorithms may fail[1], as well how and when they may be accelerated.

Subsequently, students can (and *must*) use machines to solve such smaller problems, in order to focus on bigger problems. These notions apply as much to freshmen as they do to seniors and beyond.

In fact, my attempts to articulate such thoughts has led me, for the first time in over 20 years, to write a substantial new document on what it means to teach and learn at the levels we are aspiring to:

http://robotics.ucsd.edu/teaching/Teaching_Philosophy.pdf

If there is one link that the reader of this document is going to follow, I request it be this one. The discussion in this statement speaks for itself, I believe; in fact, I view it as only a first draft of my "chapter 1" on this topic. There is much more here to say, based on the revised vision towards teaching that I am now building - I would like to find the right time and medium/venue to put these larger thoughts together in a digestible manner, perhaps during my next sabbatical.

As a military academy, my courses at USAFA are associated with military-grade oversight and extensive planning (that is, the entire plan for the semester must be fully laid out, and articulated to the cadets, before the first lecture even begins), which is new to me, and improving my workflow. See, for example, the most detailed course syllabus I have ever written for any class that I have not yet even taught, available at http://robotics.ucsd.edu/me220s/syllabus.pdf. Also, I am in the process of learning how to use Gradescope well, including rubrics for point assignments, which will allow me in the future to grade frequent student homeworks in large classes without TAs (I understand that, unfortunately, this is a new reality at UCSD…) both fairly and quickly, substantially decreasing turn-around time.

As mentioned previously, I have been asked to develop 2 courses during AY24-25. During the fall, I am teaching Mechatronics & Autonomous Systems to juniors & seniors; the way I teach it, this course is equal parts analysis, control theory, and lab-focused mechatronics. Bread and butter material for me, but it this is giving me the opportunity to substantially refine my core educational materials on these vital topics, which I teach often (take a peek at the new stuff at http://robotics.ucsd.edu/me396/).

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[1] Examples: arithmetic may become inaccurate because it is done with finite precision [e.g., $(x_{k+1} - x_k)/\Delta t$ only approximates dx/dt if Δt is not taken too small], Gaussian elimination may fail because A is singular or poorly conditioned, an eigen decomposition routine may fail because A is (nearly) defective, etc.

During spring semester, I am teaching a new “First Course in Mechanical Engineering”, designed from the ground up with a primary focus on 2D and 3D Structural System Analysis and Design. In short, I’m teaching Statics, to freshmen & sophomores. But, I’ll be throwing out most of USAFA’s existing Beer & Johnston curriculum material, which IMO is unnecessarily convoluted (because ironically the approach it takes is too simplistic), and will instead teach Statics the Stephen Timoshenko / Peter Likins way (3D first), which I initially learned from Bob Skelton, but am only now beginning to fully appreciate. I am (oddly?) excited about this opportunity (of making my own mark a freshman/sophomore-level subject). No trig! Recognize linearity, reformulate equilibrium problems (pretensionable or not) as $A\mathbf{x} = \mathbf{b}$ using automatic symbolic manipulation, and use a computer to solve. This greatly reduces the chances of error in the process. I will be teaching UCSD/MAE30b next summer, remotely, and will bring this way of teaching Statics back home. I am building up my slides at http://robotics.ucsd.edu/me220s/.

Finally, I want to point out that I have a few experimental projects going on back in my robotics lab at UCSD right now, mostly with BS and MS students, which I am joining together with developments happening here at USAFA (with undergraduate research students here), and which I plan to incorporate into my undergraduate teaching (both here at USAFA, and back home at UCSD).

The first is balloon stabilization, as discussed in my previous review, and presented at APS-DFD this year (see https://meetings.aps.org/Meeting/DFD24/Session/X33.9 for further details), including:

- the stabilization of a balloon rigged with a *single* taut ground tether (as at the San Diego Safari park) simply by coordinated actuation of this tether, in a simple (nonlinear feedback), period-doubling fashion (opposite to what a kid learns to do on a swing) to *reduce* oscillations in the wind (link), and
- the stabilization of a balloon rigged with *multiple* taut ground tethers, analyzed in a tensegrity framework, by coordinated actuation of all of the tethers, for, e.g., detailed examination of cliffs (link).

In our classroom experiments, we will use aerostats from SkyDoc, fishing line as tethers, and motorized spinning reels as winches; all are COTS. This topic builds on the foundation, including a Skelton-like analysis of tensegrity systems, that will be laid in my new freshman/sophomore-level Statics course. Note: my perspectives on this subject matured substantially during a summer faculty fellowship that I spent at JPL during spring/summer of 2019 (Dr Ryan Alimo was my host; with his introductions, I had the opportunity to meet and brainstorm with many inspiring folks at JPL).

The second is acoustic localization - a cheap, easy, and accurate way to build a table-top motion capture (aka MoCap) system, via trilateraton (not triangulation) for undergraduate teaching labs, with just four speakers (attached at the corners of a large table), two microphones (on the ends of each robot moving around on the table), and accurate timing (down to a few *micro*seconds!) of received audio chirps at the microphones on each robot using modern COTS MCUs (building, if you go all the way back, on the fundamental idea of how Newton measured the speed of sound at Trinity college).

The third is a SpaceX-style first-stage booster rocket landing demonstrator, for studying MiP-style control problems (in two orthogonal vertical planes) in flight. My students have developed an effective and affordable prototype for this problem, using counter-rotating co-linear propellors at the bottom of the vehicle instead of an actual rocket engine, which I am excited to bring online in future courses.

All three of these developments hold the promise to substantially update how I teach my core undergraduate courses in the future.

In summary, the significant service commitment that I have undertaken this year, nominally to help improve the quality of teaching in Mechanical Engineering at the US Air Force Academy, and helping to prepare the next generation USAF thought leaders for the rapidly increasing role of autonomous systems in the profession of arms, is having a substantial impact on how I view teaching engineering in general, as well as prompting me to significantly refine the specific materials (experiments, lecture slides, and supporting reading materials) that I rely on for teaching. I look forward to bringing these new perspectives and resources back home to UCSD upon my return.