Fall 2021 Personal Statement

by Prof Thomas R Bewley, *UC San Diego*

Abstract

This document provides an overview of my portfolio of recent research, teaching, and service efforts, as related to my position as a faculty member in the Department of Mechanical & Aerospace Engineering at UC San Diego.

Contents

1 Educational Robotics

1.1 Berets

One of the most unique projects to emerge from my lab, the background work for which has consumed much of my attention (and, that of my PhD student **Ricardo Gorinstein**) for the last 2 years, is the Beret family of voltage-regulation and motor-control carrier boards for robotics applications (Figure 1). Berets are designed to accelerate both research and education in controls and robotics at colleges and universities, and to streamline the lab-prototype-to-consumer-product pipeline which, as an academic, I have some unique experiences with, including the key "pain points" involved. Akin to the BeagleBone Blue, the WowWee MiP, the Renaissance Robotics eduMiP (and the follow-on myMiP, described in §1.2), all of which my lab played essential roles in developing and bringing to the educational robotics market, the (open-design) Beret family of boards is situated in something of a white space. If I am anticipating the market demand correctly, Berets might soon be as common as the Arduino and Raspberry Pi boards themselves for small robotics applications.

A succinct summary of what the Beret family of boards is all about is available **here** (note: please click anything in blue in this document for substantial further information). This link includes an introductory 34-minute video, a rotatable 3D CAD of the design, and a link to a detailed (60+ page) datasheet of the Beret family of boards, which should give some indication as to the 2 years of care put into its initial design. I believe this new "platform agnostic" family of "carrier boards" will revolutionize the speed with which students can pick up a Raspberry Pi, Qualcomm RB5, or similar Single Board Computer, and develop novel and highly functional small robotic control systems that can be quickly transformed into marketable products. We are now entering the testing phase of the first board in this series; the work has just picked up support on a gift from Qualcomm through CRI.

1.2 myMiP

The little blue eduMiPs in the display case in Jacobs Hall (Figure 2) remain in strong demand, but I have run out of stock at my little online endeavor supporting this effort, Renaissance Robotics. Rather than doing a second run of these kits, Ricardo and I have redesigned these next-gen low-cost student-owned controls labs from the ground up, to also be compatible with the full line of Berets described in §1.1; for further info on the new design (including, again, a rotatable 3D CAD), see **here**, and Figure 3. A key new feature of myMiP is that anyone with access to a computer and a 3D printer can now design their own "shells" (by modifying the getting-started CADs we provide), 3D print them, slide them on top of the myMiP frame, securely attach them with a few screws, and "bring them to life" (balance and drive, with an internal cube speaker providing its voice and/or soundtrack) in minutes, leveraging the precompiled feedback control algorithms that we provide for the corresponding boards capable of controlling myMiP. With myMiP, we are thus also providing an engaging entry-level "maker" experience that can broadly motivate high school kids towards STEM, stimulating their interest in how feedback is used to make almost all modern engineering systems work. This leads directly to further opportunities with myMiP and Berets, in college and graduate school, to develop and test practical embedded control algorithms (classical, state-space, Lyapunov-based, adaptive/learning, etc) with a consistent set of hardware, while learning how to port control codes both to more complex and capable (e.g., cellphone-based) hardware, like the Qualcomm RB5, as well as to more basic (e.g., ARM Cortex M class) hardware that is much better suited for low-cost products.

Thus, the (open-design) myMiP + Beret ecosystem is evolving into a full-fledged educational reference platform that the student can grow with over quite a number of years, from motivational 3D printing explorations in high school, through affordable (student-owned) capstone coursework in college, to research on advanced control algorithms in graduate school, and well into the product development setting.

1.3 Renaissance Robotics (RR) and Numerical Renaissance (NR)

I have doubled down on my ambitious educational effort of single-authoring the comprehensive textbook [**P5**]

Numerical Renaissance:

simulation, optimization, and control

splitting several "undergraduate-level" chapters of NR off; the (online) first edition had gotten too big (800+ pages) for one printed volume anyway. The (online, for now) second edition of NR that I am working on thus now specifically targets graduate students. The chapters cleaved from the first edition of NR are being used as some initial core material for a second (online, for now), undergraduate-level textbook, entitled [**P6**]

Renaissance Robotics:

embedding multithreaded real-time feedback into mobile robots and cyber-physical systems

My approach is that the hands-on topic of "robotics" is a significant draw for younger students, and RR will ease them into increasingly powerful analysis, simulation, and design techniques that may be applied to problems related to both stationary and mobile electromechanical systems. Motivated by several ideas brought up in RR, more mature students are ready to attack the more challenging subjects that build on advanced linear algebra and ODE/PDE simulation techniques, which is precisely where RR's companion volume, NR, begins.

Both texts are under active development. At UCSD, the chapters of RR and NR form my complete course notes for several MAE undergraduate and graduate courses, as detailed at the above two links. Note in particular that the datasheet for the Berets (see §1.1) is chapter 5 of RR, the datasheet for myMiP (see §1.2) is chapter 18 of RR, and the last several chapters of RR discuss how to bring a prototype to market (crowdfunding, injection molding, etc), all of which I bring my own unique experiences to. These two texts are accompanied by hundreds of pedagogical

Matlab codes, in both the RR codebase and the NR codebase. I intend to have this very large body of work finished (with RR and the second edition of NR available in print form) before my next academic review.

2 Transferrable Range Voting and Transferrable Approval Voting

I have also recently completed a project that reflects a unique *commitment to diversity*, of a sort which is uncommon amongst engineers. Of course, to begin with, I quite genuinely pursue the advocation of women and minorities in engineering. In a larger sense, concerned about the evident radicalization of politics in recent years, on both ends of the political spectrum, and the inviability of third parties that otherwise help to make specific minority viewpoints more clearly heard (LGBTQ rights, ethnic & racial issues, religious & nonreligious interests, ...), I have long supported the "transferrable vote" concept, as implemented by *Instant Runoff Voting (IRV)*, aka *Ranked Choice Voting (RCV)*, an idea developed over 150 years ago] and its extension, for multi-seat elections, known as *Single Transferrable Voting (STV)*, in order to evolve towards accurate proportional representation (PR) of minority interests in democratic institutions. Well (and, this is the novel component), **Prof. Paolo Luchini** and I stumbled upon an opening to do something creatively "academic" (and, hopefully, with eventual substantial real-world impact) with this passion. In particular, we have discovered and developed a pair of new voting methods, dubbed *Transferrable Range Voting (TRV)* and *Transferrable Approval Voting (TAV)*, that are perhaps the most natural extensions of the transferrable vote concept used by IRV/RCV and STV, but applied to the range voting framework (where each voter scores each candidate independently, on a absolute scale of [0,S], as we often do in academia) and the approval voting framework (where each voter simply signifies approval or disapproval of each candidate on their ballot, as we also do often in academia). The TRV and TAV methods for tabulating such elections are introduced in [**S1**], and I reckon could be broadly useful (not just in political elections, but quite likely even in faculty meetings!).

3 Coordination of wind-driven balloons

I received a JPL Summer Faculty Fellowship in 2019, during which I initiated various collaborations with JPL researchers, together with my recent PhD graduate **Ryan Alimo** (now at JPL), on various NASA-related balloon applications. The first problem we worked on [C23] was the development of a stabilized airborne platform for evaluating wave motion via "Signals Of Opportunity", looking at both incident and reflected (bouncing off the surface of a body of water) radio waves to characterize both wave motions and currents. Three other applications explored over that summer at JPL, discussed in the following three subsections, grew into much larger research efforts, as discussed below.

3.1 Stabilization of a singly-tethered balloon

Many popular destinations, including the SD Safari park, have a large helium-filled observation balloon for groups of 30-40 tourists, equipped with a single tether and a powerful winch to launch and land the balloon. Such a singly tethered balloon with a variable-length taut tether is akin to a variable-length pendulum, and as such is prone to oscillate (often, essentially, within a plane) at an angle $\phi(t)$. This angle [once distance and time are nondimensionalized by the nominal pendulum length L_0 and the characteristic time scale $\sqrt{L_0/g}$, where g is the "effective gravity" as adjusted by a classical "added mass" formulation to account for the displacement of the air that the balloon moves through] is accurately governed by the fundamental equation

$$\ddot{\phi} = -(\sin\phi + 2\,\dot{\phi}\,\dot{\ell})/\ell \quad \Leftrightarrow \quad \ell\,\ddot{\phi} + \sin\phi = -2\,\dot{\phi}\,\dot{\ell}, \tag{1}$$

which we have dubbed the "varpend oscillator", plus RHS disturbance forcing. The existing winch in such a singly-tethered balloon system can be used to modulate the pendulum length from any given reference value according to our proposed C^∞ nonlinear feedback control rule $\ell = 1 + \delta\,\phi\,\dot{\phi}$ (see [**S2**] and [**S4**]), where δ is either taken as constant, or as proportional to the inverse of a measure of the energy of the oscillations of $\phi(t)$, thus substantially subduing these oscillations (see Figure 4). This engineering application is both practically important as well as fundamental mathematically [motivating a delicate discrete-time (DT) Lyapunov-based stability analysis, currently being improved by my PhD student **Muhan Zhao**], because wind can often introduce hazardous oscillations of such balloons, forcing the system via alternate vortex shedding at frequencies near the resonant frequency of the varpend oscillator itself, akin to the Tacoma Narrows Bridge disaster that every MAE undergraduate student studies; the present control strategy can be used to subdue such oscillations before they get too large, thus preventing future such disasters.

3.2 Stabilization of a multiply-tethered balloon/payload system

Much of the rich geological history on Earth and other planetary bodies is best revealed in the highly stratified sedimentary rocks exposed in steep cliffs. In addition, certain unique biological specimens on Earth, and noteworthy transient environmental features on Mars, also occur only within cliffs and steep tallus slopes; studies of such phenomena are instrumental in the search for liquid water on or near the surface of Mars.

Substantial ongoing research is thus devoted to the autonomous exploration of steep cliffs, primarily using vehicles that either free climb from below using advanced rock grippers, or descend from above via controlled rappel. Unfortunately, both free climbing (up from below) and rappelling (down from above) are highly delicate maneuvers, with potentially dire consequences (both to the robot, and to the delicate biological objects or environmental features under consideration) for any misstep. The JPL Mars 2020 mission introduced the remote operation of an unmanned helicopter (a.k.a. drone) on Mars, albeit with a 3 minute maximum mission duration. Such drones might also be considered for further exploration of interesting areas unreachable by conventional rovers; however, with their limited payload capacity and mission duration, the extent of the remote exploration that drones can be expected to perform on Mars is anticipated to be quite limited.

Remarkably, many otherwise difficult-to-reach areas (cliffs, tallus slopes, crater walls, sinkholes, etc) on Earth, Mars, and Titan are readily made safely accessible for sustained close inspection (imaging, sampling, drilling, etc) by stabilized measurement platforms suspended from balloons stabilized by multiple taut ground tethers (Figure 5).

Such systems may be analyzed by certain natural extensions of the tensegrity framework pioneered by MAE's own **Bob Skelton** and **Mauricio de Oliveira**. Specifically, I have shown (see [**S3**] and [**S5**]) how to incorporate solid bodies into a tensegrity structure, and how to handle structures that are not *pretensionable*, but are in fact, over a certain finite range, *tensionable under load* (once the lift of the balloon and the weight of the payload are incorporated), with static tensioning optimized via a remarkably efficient Linear Programming (LP) approach, and with the dynamics of the embedded solid bodies modelled via a quaternion formulation (naturally extending the approach developed by Bob and Mauricio for handling the bars of a tensegrity structure, *without* requiring the computation of expensive trigonometric functions). The redundant tethers in such systems may thus be coordinated by feedback in order to stabilize such a balloon-suspended remote observation platform for the sustained detailed study of features on the cliffs of Earth and Mars (and, maybe someday, Titan). [Note that preliminary approaches to this feedback control setting have been explored by my recent visiting student **Thomas Claudet**, from École Polytechnique in France, as discussed in [**C25**], though much future work work remains to be done.]

3.3 Coordination of sensor balloon swarms in hurricanes

The problem of seeding a swarm of $n = O(100)$ sensor- and radio-equipped buoyancy-controlled *untethered* balloons into hurricanes, to assist in the (real-time) hurricane forecasting problem, is a keen interest of mine, and has been pioneered by my lab. As proposed in [**C9**] (though much future experimental work remains), such balloons can be:

- constructed using existing (puncture-resistant, gas impermeable) material technologies,
- produced using existing designs for sufficient control authority over the vehicle buoyancy for the target application,
- compact folded, and subsequently deployed (and, reliably auto-inflated) using existing chutes (currently used for deploying dropsondes) in existing NOAA aircraft,
- expected to survive for days at a time in the challenging (turbulent, wet, cold) environment of a hurricane, and
- safely landed by NOAA, and retrieved and returned to NOAA (for a suitable "finders fee") by "citizen scientists", after the hurricane makes landfall and quickly dissipates.

Note that the sensor balloons (which will be mass produced to drive costs down) have GPS and radios, so their locations after they land can easily be identified by NOAA and (for those not landing in sensitive areas) posted online, providing a (possibly, fun, if properly publicized) geocaching adventure for motivated amateurs. Future work will also explore how balloons designed to be deployed into such harsh environments can scavange energy from the (highly turbulent) flowfield into which they are introduced, in order to keep their batteries charged.

When balloons are deployed into a hurricane, they essentially settle into certain equilibrium altitudes (as established by their buoyancy, which is controllable), with mostly minor fluctuations, while they act like flow tracers (aka Lagrangian particles) in the (100+ mph) horizontal winds, generally moving them around the hurricane core.

In this setting, recording the positions and velocities of the balloons (as measured by their GPS units and IMUs), and relaying appropriate summaries of this data back to NOAA shortly after it is obtained, provides a trove of high quality, highly relevant in situ information on the hurricane flowfield (which is otherwise difficult to accurately measure, especially out over the ocean) that can substantially improve real-time forecasts of the track and intensity of the hurricane, the accuracy of which are essential for saving lives and property when urban areas are threatened.

3.3.1 Large-scale coordination of the swarm

A bulk description of the mean flowfield of a well-developed hurricane is sufficient to motivate why this scheme works: this mean flowfield is generally directed *in* at low altitudes, *up* at the eyewall, and *out* at high altitudes (and, when viewed from above, circulates 'round and 'round the core, at enormous velocities). Noting this, there is a natural "restoring force" available which makes the coordination of a balloon swarm in this setting possible: if ever an individual balloon strays too far from the hurricane core, the coordinating algorithm can simply command it to move *down*, after which it will be blown back *in*, towards the hurricane core. This control authority can be leveraged quite efficiently in the model predictive control (MPC) setting, as introduced broadly to the scientific community in our plenary lecture at 2015 APS-DFD conference, discussed further in our associated seminal paper on the subject [**J4**], and demonstrated in two associated animations, available **here** and **here** (see Figure 6).

3.3.2 Ad hoc radio network

In the application envisioned, an ad hoc mesh of low-power radio links, arranged like forked spokes, emanate from a central "mothership", located in the eye of the hurricane, equipped with a satellite uplink for relaying the measured data (from the sensor balloons, which are of course located at a wide range of different distances from the hurricane core) back to NOAA headquarters. The individual radio links in this low-power ad hoc radio network are only 10-15 miles each (and, line-of-sight, in a geographic region where there generally isn't any interference whatsoever from other radios), even though a typical strong hurricane is well over 100 miles in radius. This ad hoc mesh must also be reconnected frequently, as balloons at different distances from the core have significantly different orbital periods. Much future work is needed to work out the details of how this large-scale mesh network can best be implemented and maintained. Note that there is a 3-way tradeoff in the optimization problem related to coordinating the balloons:

• the vehicles should command as *few vertical movements as possible* in order to conserve energy,
• the vehicles generally need to move *far from each other*, to better observe different parts of the flowfield, but
• the vehicles also generally need to *stay close enough to each other* that communication links remain reliable, and can be established and maintained at relatively low levels of transmission power.

That is, optimization of the "underactuated" (that is, vertical) motions of the vehicles is a delicate balance between the "move to observe better" problem and the "move to communicate better" problem, which generally have competing requirements. Much future work remains to better understand this particular class of control problems. Note in particular that, if/when one part of the network becomes disconnected from another, a balloon acting as a *data mule* can buffer the available data to be transmitted, and physically move into a region with radio access (via the mesh network) to the mothership.

3.3.3 Smaller-scale disturbance rejection

The smaller-scale disturbance rejection problem is also interesting. Our central strategy related to small-scale disturbances is, most of the time, do nothing, just ride them out. However, if (due to random fluctuations) the balloon wanders too far from its desired position in a "formation" of $m \ll n$ balloons orbiting the core of the hurricane at a certain radius (on a zero-radial-velocity manifold within the mean hurricane flowfield), an appropriate vertical shift of the balloon (causing the balloon to move either *up* and *out* on this manifold, increasing its orbital period, or *down* and *in* on this manifold, decreasing its orbital period) can be used to redirect the balloon back to its desired azimuthal location in the formation. Our seminal work on this fascinating problem is described in [**C4**] and [**J9**].

To make it tractable, the work described in the paragraph above is based on a simple stochastic model for the *positions* of the balloons in the formation, to evolve with a statistical "random walk" away from those planned by the coordinating MPC formulation. Upon closer inspection, this model does not well match how a Lagrangian tracer would move within a turbulent flowfield. A much better stochastic model for the motion of a Lagrangian particle in turbulence (dating back to an analysis by Tennekes, in a 1975 *JFM* paper) is for the *velocities* of the balloons to evolve with a statistical random walk. This remarkable reformulation of the present analysis was introduced in [**A2**] and [**A4**], and was discussed at length in my March 2019 seminar at GALCIT [**A3**], the slides of which, which are fairly self-explanatory and well describe the essence of this problem, are available here. The essential results of this analysis, which will be much more broadly announced in (ongoing) future work, [**P3**] and [**P4**], are twofold:

1. The first result is a new stochastic model for turbulence, in which the starting-point axiom, of describing a turbulent flowfield as a sum of a (stationary or nearly stationary) mean component plus a (statistically stationary) fluctuation component, is fundamentally revisited.
2. The second result is a spontaneously singular (on/off) control rule that arises in this setting organically (and, quite surprisingly), from a smooth control formulation with a nonquadratic objective.

As far as I know, there is nothing like result 1 in the existing literature in fluids, there is nothing like result 2 in the existing literature in controls, which is itself pretty exciting.

3.3.4 Summary of the overarching problem of coordinating sensor balloon swarms in hurricanes

With global climate change (and concomitant increases in severe weather activity) now established as scientific fact, and populations densities ever increasing along coastlines, accurate hurricane forecasting is increasingly important. To make significant progress, the thing that is most needed, even more than both improved state estimation (aka "data assimilation") algorithms and faster supercomputers, is better in situ data about the hurricane. The present overarching research thrust presents, I believe, the most natural and (by far) most cost effective way of getting such data, sustained over the entire adult life of the hurricane. Note that, in sharp contrast with the use of dropsondes, the entire swarm of balloons in this application may be deployed from single flight over a developing hurricane (with existing NOAA aircraft, through existing chutes built into such aircraft). This is relevant because the flights themselves are currently one of the most expensive aspects of deploying in situ sensor devices into hurricanes.

Again, the big picture here is to occasionally command limited vertical motions of the balloons in the swarm, using buoyancy control only (in an energetically efficient manner), in order to coordinate the rapid horizontal motions of the balloons in the swarm within the highly-vertically-stratified hurricane flowfield. The goal is to well distribute the balloons over the hurricane, and to shift the balloons with the hurricane as it translates accross the ocean. Monitoring the resulting motion of the balloons (which act like flow tracers within the hurricane, "going with the flow", so to speak; again, see the animations linked in §3.3.1), in order to better estimate the current state of the hurricane, and thus to better forecast its future track and intensity (specifically, where it will make landfall, and how intense the hurricane and corresponding storm surge will be when it gets there).

While we have made very promising initial progress on some of the key questions related to this overarching problem, as documented in the several papers linked above, my lab is still seeking the large-scale funding necessary to make this ambitious vision a reality. I am committed to making this happen, and am hoping that some of my new contacts at JPL can help. As highlighted above, much future work remains to be done. As my mentor Bob Skelton spent the last 20 years of his academic career studying tensegrity systems in a control-oriented framework, I imagine that, of all of the interesting reserach directions summarized in this document, this is the one that I will focus on the most in the last 20 years of my own academic career, inshallah, and if future funding allows.

4 Efficient derivative-free global optimization of nonconvex functions

The problem of optimizing a handful of parameters (within a bounded "feasibility domain", that may be known or unknown at the outset), based on available data, is ubiquitous in engineering, science, finance, operations research, politics, and many other fields.

As computers get faster, but the "function evaluations" considered in any given domain (an experiment, a big simulation, etc) remain expensive, the focus in the optimization problem turns to maximizing its speed of convergence (minimizing the number of function evaluations required), while at the same time providing a level of assurance that the vicinity of the global minimum has been discovered. This delicate balance is referred to as the compromise between *global exploration* and *local refinement*. Effectively, it boils down to "squeezing" the absolute most information possible about the underlying (often, analytically unknown, and possibly nonsmooth) function being optimized, as well as the remaining uncertainty about this function, over the entire feasible domain being considered, subject to some precisely-defined "reasonable" assumptions about the continuity of the underlying function being optimized. That is, the algorithm must identify properly the *trends* evident in the function evaluations available thus far, and model its *uncertainty about these trends*, at each step as the algorithm proceeds.

There are many available algorithms for this class of problems; some (genetic algorithms, simulated annealing, etc.) are outdated and inefficient, while others (downhill simplex, generalized pattern search, etc.) achieve only local convergence. One existing method, the *surrogate management framework* (SMF, as reviewed by Jones et al), shone brighter than all others when we began to take our own new look at this old problem, about 10 years ago. SMF, which models both the underlying (unknown) function, as well as the current uncertainty about this model, with a Kriging interpolant, is definitely on the right track in terms of achieving the desired balance between global exploration and local refinement, as reviewed above. However, a closer look motivates many difficult and substantial improvements, in order for this general approach to "be all it can be" for a wide variety of distinct problem formulations.

Achieving the required balance between global exploration and local refinement motivates a fascinating integration of rigorous mathematical proofs and tools [Delaunay triangulations, dense sphere packings, etc] and carefully designed heuristics [maximally smooth interpolation strategies (in many situations, Kriging breaks down entirely), piecewise quadratic uncertainty models, restriction to Cartesian or noncartesian grids, etc].

My team (recent PhD graduates **Pooriya Beyhaghi** and **Ryan Alimo**, and current PhD student **Muhan Zhao**) has fundamentally revisited the SMF based on these several ideas, developing an entirely new class of derivative-free optimization algorithms that are designed to squeeze the most information possible about the function being optimized, and the current uncertainty about that function, over the feasible domain being considered, based on the function evaluations available at each step. We call our (extensive) set of algorithms for this general class of problem *Derivative-free Optimization via Global Surrogates (DOGS)*. Our seminal paper on this subject is:
[**J6**] Delaunay-based derivative-free optimization via global surrogates, part I: linear constraints.

A series of four papers (listed below) then refined the types of constraints considered, which was intricate. In the third case, the constraints are not known in advance, and are only discovered as the problem proceeeds, and the "function evaluator" returns "infeasible" flag. In the fourth case, the constraints are again unknown in advance, and we consider the problem of "safe" optimization, in which something physical will possibly break (a UAV will crash, etc) if a function evaluation is attempted with bad parameters. In this formulation, the region in parameter space that is allowed to be explored next is based on existing knowledge of how previous function evaluations have fared.
[**J7**] Delaunay-based derivative-free optimization via global surrogates, part II: convex constraints.
[**J10**] Delaunay-based derivative-free optimization via global surrogates. Part III: nonconvex constraints.
[**C16**] Delaunay-based global optimization in nonconvex domains defined by hidden constraints.
[**C15**] Delaunay-based Derivative-free Optimization via Global Surrogates with Safe and Exact Function Evaluations.

The problem of derivative-free optimization, in general, suffers from a "curse of dimensionality". We thus considered four distinct approaches (listed below) to accelerate our original algorithm, including (a) restriction to grids, to keep function evaluations appropriately separated in parameter space as convergence is approached, while using efficient grid-based local refinement methods leveraging minimal postive bases on such grids, (b) improved interpolation strategies, (c) reducing the dimension of the problem considered for a while during the global search, if certain dimensions prove to be "less important", and (d) derivative-based local refinement, for the special case of optimizing analytically known, differentiable, but highly nonconvex functions.
[**J8**] Implementation of Cartesian grids to accelerate Delaunay-based derivative-free optimization.
[**C7**] Delaunay-based optimization in CFD leveraging multivariate adaptive polyharmonic splines (MAPS).
[**C10**] An active subspace method for accelerating convergence in Delaunay-based opt. via dimension reduction.
[**C8**] Optimization combining derivative-free global exploration with derivative-based local refinement.

Finally, a set of three more papers (listed below) considered the framework of minimization of functions that are obtained via statistical averaging. One example application here (of many) is the computation of the time-averaged drag in a highly-resolved simulation of a turbulent flow, and a corresponding attempt at minimizing this drag, by optimizing a handful of parameters defining the compliance properties of the surface underlying this flow. This is a computational grand challenge application for which I received my ONR YIP award many years ago, but which I am only now really discovering how to address properly algorithmically. The starting point notion here is that there is no need to solve an approximate problem exactly. That is to say, early on in the optimization, a small amount of statistical averaging is sufficient to effectively "rule out" various large regions in parameter space as less than promising. As convergence is approached, new function evaluations (and, certain existing function evaluations) need to be refined further, in order to know the statistically-averaged function of interest corresponding to that location in parameter space with greater certainty. The resulting algorithm we have developed here is unique; AFAIK, no other research group looking at global optimization algorithms has developed a rigorous (mathematically-justified) method of automatically tuning the fidelity of function evaluations as convergence is approached, for the important problem of optimizing functions that are obtained via statistical averaging.
[**J11**] A derivative-free optimization algorithm for the efficient minimization of fns. obtained via statistical averaging.
[**C21**] A Delaunay-based method for optimizing infinite time averages of numerical discretizations of ergodic systems.
[**P1**] Uncertainty Quantification of the time-averaged statistics derived from a numerical sim. of a turbulent flow.

Our unique DOGS framework of optimization algorithms is now fairly mature, with a bit more future work planned in the area of safe optimization, and in the area of the optimization of functions obtained via statistical averaging. Potential applications are enormous; two practical examples that have already demonstrated its effectiveness include [**C7**], cited above, which optimized the parameters defining a hydrofoil on an America's cub yacht, and [**J12**], cited in §6.3, which optimized the parameters defining advanced IMEXRK algorithms for time advancement of stiff ODEs.

A few years from now, after I publish RR and NR in print form and get their corresponding github repositories of pedagogical codes reasonably complete, I plan to sit down and begin a new book that threads this entire story together, as a third substantial text in the Renaissance series. That should be rewarding and impactful; the big picture here is really a bit to large for people to get their arms around from the dozen separate articles linked above (plus the few that remain to be written).

5 Coordination of UAV/USV teams

As a former member of the US armed forces (as a lieutenant and pilot in the USAF), I also have a passion for keeping our soldiers safe. In particular, when conducting stealthy ISR (intelligence, surveillance and reconnaissance) operations off the coastline in potential conflict zones (North Korea, Russia/Ukraine, China/Taiwan, Persian Gulf, etc), if autonomous systems are used appropriately, there is really no need to put our soldiers in harm's way. To me, that represents an awesome opportunity (and, responsibility) for performing impactful relevant research.

I thus have a close connection with several folks in the robotics branch at SPAWAR (now NIWC Pacific), and via that connection am always on the lookout for impactful new robotics projects to work on. The main project we are now working on together involves the coordination of UAV/USV teams for ISR, which has grown to be a rather substantial activity. This project is led by my recent PhD graduate **Kurt Talke** (who also works for the US Navy at NIWC Pacific, and will be giving a seminar in MAE on this work in January), and the project is now also being picked up by current PhD students **Joonyoung Jang** (an officer in the South Korean Navy) and **Miguel Angel Martinez** (a Mexican citizen), all three of whom were/are supported on full-ride PhD scholarships to UCSD.

The overarching problem considered in this research thrust starts with the deployment of a Unmanned Surface Vehicle (USV), about the size of a Mastercraft, with a generator capable of producing substantial electric power (at high voltage) for a long period of time. Protected within a bay on the deck of this USV is a large power-hungry UAV, with ISR equipment that needs to operate a few hundred feet up for increased range (line of sight to the horizon). The USV can be autonomously piloted out to a desired monitoring location, open its bay doors, launch the UAV, and stay on station at the specified monitoring location. So far, this is all pretty easily doable with existing Navy technologies, even in GPS-denied environments (which must be assumed in conflict zones).

Now, the interesting part: the UAV is designed to operate on a tether from the USV (see Figure 7). Power is provided from the USV, over this tether, to the UAV, thus enabling sustained operations of the ISR equipment on the UAV. Further, there may be high seas (up to sea state 4). In this scenario, the USV is bobbing up and down (up to several feet), while the UAV needs to hover at an approximately constant altitude. Thus, a winch on the USV uses feedback control to maintain the tether in a semi-slack state, neither tugging at the UAV when the USV moves down into a wave trough, nor dragging into the water (and, potentially, fouling on kelp, or the USV itself) when the USV moves back up on a wave crest. Note that all existing COTS solutions used by the DoD for tethered management of UAVs keep the tether taut. In sharp contrast, our new approach maintains the tether (leveraging carefully-designed feedback control, in a GPS-denied setting) in a "semi-slack" state, thereby reducing the downforce on the UAV, thus improving its capabilities and operational envelope (robustness to heave of the USV), greatly increasing the maximum possible payload, flying height, and mission duration. This practical control problem is actually much harder than it sounds. Our inital work on this problem is described in the following four papers:
[**C11**] Catenary tether shape analysis for a UAV-USV team.
[C19] Design and parameter optimization of a 3-PSR parallel mechanism for replicating wave and boat motion.
[**S7**] Autonomous Hanging Tether Management and Experimentation for an Unmanned Air - Surface Vehicle Team.
[**P2**] On dynamics and numerical simulation of a three-dimensional elastic string pendulum.

Still unpublished are some half-scale experiments that Kurt performed a couple of months back at an amazing test facility in the Naval Sea Systems Command in Carderock, Maryland; hopefully these results will soon be cleared for public release (working with the government, clearance for release of such results can take a while).

Joon is following up on this work by building a (tensegrity-based) motion simulator (for an example of such a device, see here), that we are aiming to eventually build, at full scale, and install in the UCSD Aerodrome, to experimentally perfect autonomous landing of a UAV on the deck of a pitching USV.

Meanwhile, Angel is working on the challenging problem of "pose estimation" of the deck of the USV (that is, estimation of its pitch, roll, yaw, surge, sway, and heave) based solely on camera observations by the UAV of a set of lights on the deck of the USV at known locations.

6 Other research activities

As can be seen in the above discussion, the heart of my research focus is on Flow Control (these days, more accurately, on the control of objects within a flow, often to help estimate the flow itself) and Coordinated Robotics. I am particularly interested in overarching problems that I find at the intersection of these two large areas, as discussed in §3.1, §3.2, §3.3, and §5.

Several other smaller projects are also ongoing in my lab, which are too numerous to provide much background about here. I will thus simply group these projects together by general subject area below, and ask the reader to follow the links to read the abstracts of any particular subject area (accurately described by the corresponding paper titles) that he/she finds to be interesting. These abstracts are each just a click away...

6.1 Flow control

Essential team members represented here include former UCSD PhD student **Daniele Cavaglieri** and our frequent sabbatical visitor, from UNISA Italy, **Prof Paolo Luchini**.

[**C1**] MPC leveraging Ensemble Kalman forecasting for optimal power take-off in wave energy conversion systems.
[**J5**] Methods for solution of large optimal control problems that bypass open-loop model reduction.
[**A1**] Implementation of boostconv to accelerate the oppositely-shifted subspace iteration (OSSI) method for approximate optimal control without model reduction.

6.2 Coordinated robotics

Essential team members represented here include UCSD PhD students **Jeff Friesen**, **Daniel Yang**, **Pengcheng Cao**, and former PhD students **James Strawson**, **Nick Morozovsky**, and **Eric Sihite**, as well as our frequent collaborators, **Prof Falko Kuester** and **Dr Clark Briggs**.

6.2.1 Hardware design

[C5] The second generation prototype of a Duct Climbing Tensegrity robot, DuCTTv2.
[C12] A Tensegrity-Inspired Compliant 3-DOF Compliant Joint.
[C13] A minimalist Stair Climbing Robot (SCR) formed as a leg balancing & climbing Mobile Inverted Pendulum.
[**C2**] Design and control of a micro ball-balancing robot (MBBR) with orthogonal midlatitude omniwheel placement.
[**C26**] Monocoque Multirotor Airframe Design with Rotor Orientations Optimized for 6-DoF UAV Flight Control.
[**C27**] Rotor orientation optimization for direct 6 degree of freedom control of multirotors.

6.2.2 Development of algorithms for modeling, estimation, control, and coordinated motion

[J2] Stair Climbing via Successive Perching
[C14] Attitude estimation of a high-yaw-rate Mobile Inverted Pendulum; comparison of Extended Kalman Filtering, Complementary Filtering, and motion capture.
[C18] Modeling and state estimation of a Micro Ball-balancing Robot using a high yaw-rate dynamic model and an Extended Kalman Filter.
[C28] Decoupled translational and rotational flight control designs of canted-rotor hexacopters.
[**C17**] Derivation of a new drive/coast motor driver model for real-time brushed DC motor control, and validation on a MIP robot.

[**C22**] A Probabilistic Path Planning Framework for Optimizing Feasible Trajectories of Autonomous Search Vehicles Leveraging the Projected-Search Reduced Hessian Method.
[C24] Point Cloud-Based Target-Oriented 3D Path Planning for UAVs.

6.2.3 Education-focused efforts

[C3] Leveraging Open Standards and Credit-Card-Sized SBCs in Embedded Control & Robotics Education.
[C6] Extending Low-Cost Linux Computers for Education and Applications in Embedded Control and Robotics.
[C20] A systems engineering Persistence Of Vision teaching module integrating coordinated sensing, actuation, multithreaded computation, custom PCB design, and inductive power transfer.
[C29] BeagleRover: An Open-Source 3D-Printable Robotic Platform for Engineering Education and Research.

6.3 High-performance computing

[**J1**] Low-storage implicit/explicit Runge–Kutta schemes for the simulation of stiff high-dimensional ODE systems
[**J12**] Design of IMEXRK time integration schemes via Delaunay-based derivative-free optimization with nonconvex constraints and grid-based acceleration.
[**S6**] Tweed and wireframe: accelerated relaxation algorithms for multigrid solution of elliptic PDEs on stretched structured grids.

6.4 Miscellaneous

[S8] A general method for direct elementary construction of compact C^∞ sigmoid functions.
[J3] Optimization of Drug Delivery by Drug-Eluting Stents.

7 Summary

I am loath to have my research contributions characterized by a blind "tally", summarizing with a single real number how the references enumerated in my recent bibliography, below, are deemed to "count"; for example, taking

$$\begin{aligned}\text{tally} = (\#\text{ of }\underline{\text{J}}\text{ournal articles}) + [\#\text{ of }\underline{\text{C}}\text{onference papers, each weighted by }\alpha_c] + 0\times\ (\#\text{ of }\underline{\text{A}}\text{bstracts}) +\\ 0\times\ (\#\text{ of }\underline{\text{S}}\text{ubmitted manuscripts}) + 0\times\ (\#\text{ of works in active }\underline{\text{P}}\text{reparation}) + 0\times\ (\#\text{ of patents}),\end{aligned} \tag{2a}$$

where $0 < \alpha_c < 1$. Such a tally indicates, perhaps, the degree to which one has kept busy, but does not accurately represent the significance of one's research activities. If such a tally were done for me for the bibliography provided below (12 journal papers + 29 conference articles published from 2015 to present), this might be written

$$\text{tally} = 12 + [\alpha_{\text{CDC}} \times 3 + \alpha_{\text{ACC}} \times 1 + \alpha_{\text{ICRA}} \times 4 + \alpha_{\text{IROS}} \times 3 + \alpha_{\text{other}} \times (29-11)] + 0\times 4 + 0\times 8 + 0\times 6 + 0\times 5, \tag{2b}$$

noting that α_{CDC}, α_{ACC}, α_{ICRA}, α_{IROS} are probably each pretty close to unity, as their rejection rates are higher than many journals. However, I believe that the mere act of performing such a tally entirely misses the point. As an MAE professor, I would much rather have each of my contributions considered by the product of

A. some measure of the analytic or algorithmic or design originality and effectiveness of the approach taken, times
B. some measure of the potential future impact of the work in the real world, outside of academic halls.

Those results that are lacking in measure A might lead to useful product development (and, may be patentable), but don't lead to a substantial rethinking of the subject considered, whereas those results that are lacking in measure B (which are perhaps suitable for a pure mathematician or theoretical physicist) might lead to satisfying new perspectives, but have no substantial impact on the human condition.

In this regard, most of the projects discussed earlier in this document are, IMO, both rich in measure A (based on the new thinking that we have brought to these problems) and are also high in measure B, with strong probability for substantial real-world impact, which is why I have incorporated them into my research portfolio. Specifically:

• The clever new vote tallying methods we have developed, TRV and TAV, represent our sincere efforts in establishing proportional representation of diverse minority viewpoints in democratic institutions.
• The stabilization of singly-tethered observation balloons enjoyed by tourists, using a smooth nonlinear control strategy (analyzed with DT Lyapunov methods) implemented with the existing winch in such systems, might well lead to the prevention of sympathetic wind-driven oscillations that might otherwise cause such systems to crash.
• The stabilization of multiply-tethered balloon/payload systems, enhancing and building upon the framework of tensegrity systems analysis established by Bob Skelton and coworkers, is aimed at developing stable new observation platforms for the scientific study of features on steep cliffs, both on Earth and on Mars.
• The development and coordination of sensor balloon swarms for dense in situ measurements of hurricanes, an overarching problem with a rich array of engineering, communication, modeling, and control challenges to be overcome, will (if actually implemented) lead directly to substantially improved forecasts of the track and intensity of hurricanes and their associated storm surge, which is vital to both protect property and save lives.
• The problem of maximizing the efficiency of derivative-free global optimization algorithms calls for the careful integration of mathematically elegant analysis and tools, and carefully designed heuristics. This class of problems is of direct relevance for the optimization of engineering designs using computer simulations in a vast array of practical applications across essentially all engineering disciplines.
• The coordination of UAV/USV teams, for operating stealthy ISR systems off the coastline of potential conflict areas without putting our soldiers in harm's way, represents one of our best efforts towards making this dangerous world a bit safer place to live.
• The general subject of "educational robotics" (Berets, myMiP, RR/NR) represent our efforts towards inspiring new generations of researchers, who will be left (by my generation) with *many* hard problems remaining to be solved.

Finding projects that are high in measure B, identifying approaches (based on one's unique academic background) that are also high in measure A, is of course quite difficult. Admittedly, not all of my own research activities shine according to this characterization (as an example, I believe that [S8] is quite lacking in measure B...). It is, I believe, the (difficult) job of the reviewer to characterize, in balance, the core projects of the academic reviewee (in this case, me) in terms (for those in the applied field of Mechanical and Aerospace Engineering) of both measure A *and* measure B. I hope the sections provided earlier in this document have helped in this necessarily fairly subjective undertaking. Note finally that my academic career is still very much a "work in progress"; several related deep and important research questions have come up in the above investigations, only some of which have been specifically called out as future work in this document. Please feel free to contact me with any follow-up questions.

References

Please click on any reference title highlighted in blue for a direct link to the corresponding article online. Note that [Jx] denotes a journal article, [Cx] a conference paper, [Ax] an abstract, and [Px] a preprint; those references with particularly creative new analyses are tagged in **bold**. Organized by year, from 2015 to present.

[**J1**] Cavaglieri, D, **Bewley, T** (2015) Low-storage implicit/explicit Runge–Kutta schemes for the simulation of stiff high-dimensional ODE systems *Journal of Computational Physics* **286**, p. 172-193.

[J2] Morozovsky, N, **Bewley, T** (2015) Stair Climbing via Successive Perching *IEEE Transactions on Mechatronics* **20** (6), p. 2973-2982.

[J3] Bozsak, F, Gonzalez-Rodriguez, D, Sternberger, Z, Belitz, P, **Bewley, T**, Chomaz, J-M, Barakat, A (2015) Optimization of Drug Delivery by Drug-Eluting Stents *PLoS ONE* **10** (6), p. 1-29.

[**C1**] Cavaglieri, D, **Bewley, T**, Previsic, M (2015) Model Predictive Control leveraging Ensemble Kalman forecasting for optimal power take-off in wave energy conversion systems. *American Control Conference*, p. 5224-5230.

[**C2**] Yang, D, Sihite, E, Friesen, J, **Bewley, T** (2015) Design and control of a micro ball-balancing robot (MBBR) with orthogonal midlatitude omniwheel placement *IEEE Conference on Intelligent Robots and Systems (IROS)*, p. 4098–4104.

[C3] **Bewley, T**, Strawson, J, Briggs, HC (2015) Leveraging Open Standards and Credit-Card-Sized Linux Computers in Embedded Control & Robotics Education. *AIAA Structures, Structural Dynamics, and Materials Conference*, AIAA 2015-0801, p. 1-6.

[**J4**] **Bewley, T**, Meneghello, G (2016) Efficient coordination of swarms of sensor-laden balloons for persistent, in situ, real-time measurement of hurricane development. *Physical Review Fluids* **1** (6), 060507, p. 1-14.

[**J5**] **Bewley, T**, Luchini, P, Pralits J (2016) Methods for solution of large optimal control problems that bypass open-loop model reduction. *Meccanica* **51** (12), p. 2997-3014.

[**J6**] Beyhaghi, P, Cavaglieri, D, **Bewley, T** (2016) Delaunay-based derivative-free optimization via global surrogates, part I: linear constraints. *Journal of Global Optimization* **66**, p. 331–382.

[**J7**] Beyhaghi, P, **Bewley, T** (2016) Delaunay-based derivative-free optimization via global surrogates, part II: convex constraints. *Journal of Global Optimization* **66**, p. 383–415.

[**C4**] Meneghello, G, Luchini, P, **Bewley, T** (2016) On the control of buoyancy-driven devices in stratified, uncertain flowfields. *VIIIth Int. Symp. on Stratified Flows, San Diego*, p. 1-6.

[C5] Friesen, J, Glick, P, Fanton, M, Manovi, P, Xydes, A, **Bewley, T**, Sunspiral, V (2016) The second generation prototype of a Duct Climbing Tensegrity robot, DuCTTv2 *International Conference on Robotics and Automation (ICRA)*, p. 1-6.

[C6] Briggs, HC, Strawson, J, **Bewley, T** (2016) Extending Low-Cost Linux Computers for Education and Applications in Embedded Control and Robotics. *AIAA Structures, Structural Dynamics, and Materials Conference*, AIAA 2016-0825, p. 1-12.

[**J8**] Beyhaghi, P, **Bewley, T** (2017) Implementation of Cartesian grids to accelerate Delaunay-based derivative-free optimization. *Journal of Global Optimization* **69**, p. 927–949.

[**C7**] Alimo, S, Beyhaghi, P, Meneghello, G, **Bewley, T** (2017) Delaunay-based optimization in CFD leveraging multivariate adaptive polyharmonic splines (MAPS). *AIAA Structures, Structural Dynamics, and Materials Conference*, AIAA 2017-0129, p. 1-16.

[**C8**] Alimo, S, Beyhaghi, P, **Bewley, T** (2017). Optimization combining derivative-free global exploration with derivative-based local refinement. *IEEE Conference on Decision and Control (CDC)*, p. 2531-2538.

[**C9**] Meneghello, G, **Bewley, T**, de Jong, M, Briggs, HC (2017) A coordinated balloon observation system for sustained in-situ measurements of hurricanes. *IEEE Aerospace Conference*, p. 1-6.

[**J9**] Meneghello, G, Luchini, P, **Bewley, T**, Pralits J (2018) A probabilistic framework for the control of systems with discrete states and stochastic excitation. *Automatica* **88**, p. 113-116.

[**C10**] Zhao, M, Alimo, S. R, **Bewley, T** (2018). An active subspace method for accelerating convergence in Delaunay-based optimization via dimension reduction. *IEEE Conference on Decision and Control (CDC)*, p. 2765-2770.

[**C11**] Talke, K, de Oliveira, M, **Bewley, T** (2018) Catenary tether shape analysis for a UAV-USV team. *IEEE Conference on Intelligent Robots and Systems (IROS)*, p. 7803–7809.

[C12] Friesen, J, Dean, J, **Bewley, T**, Sunspiral, V (2018) A Tensegrity-Inspired Compliant 3-DOF Compliant Joint *International Conference on Robotics and Automation (ICRA)*, p. 3301–3306.

[C13] Yang, D, **Bewley, T** (2018) A minimalist Stair Climbing Robot (SCR) formed as a leg balancing & climbing Mobile Inverted Pendulum (MIP) *IEEE Conference on Intelligent Robots and Systems (IROS)*, p. 2464–2469.

[C14] Sihite, E, **Bewley, T** (2018) Attitude estimation of a high-yaw-rate Mobile Inverted Pendulum; comparison of Extended Kalman Filtering, Complementary Filtering, and motion capture. *American Control Conference (ACC)*, p. 5831-5836.

[**A1**] **Bewley, T**, Luchini, P (2018) Implementation of boostconv to accelerate the oppositely-shifted subspace iteration (OSSI) method for approximate optimal control without model reduction. Abstracts of the *13th ERCOFTAC SIG 33 Workshop, Progress in Flow Instability, Transition and Control*, March 6-8, Paraty, Brazil, p. 33.

[**A2**] Luchini, P, **Bewley, T**, Meneghello, G (2018) Optimal guidance of buoyancy-controlled balloons in turbulent flows using a nonquadratic objective and discontinuous actuation. Abstracts of the *13th ERCOFTAC SIG 33 Workshop, Progress in Flow Instability, Transition and Control*, March 6-8, Paraty, Brazil, p. 34.

[**C15**] Zhao, M, Alimo, S, Beyhaghi, P, **Bewley, T** (2019) Delaunay-based Derivative-free Optimization via Global Surrogates with Safe and Exact Function Evaluations. *IEEE Conference on Decision and Control (CDC)*, p. 4636-4641.

[**C16**] Alimo, S, Beyhaghi, P, **Bewley, T** (2019) Delaunay-based global optimization in nonconvex domains defined by hidden constraints. In *Evolutionary and Deterministic Methods for Design Optimization and Control With Applications to Industrial and Societal Problems*, p. 261-271. Springer.

[**C17**] Sihite, E, Yang, D, **Bewley, T** (2019) Derivation of a new drive/coast motor driver model for real-time brushed DC motor control, and validation on a MIP robot. *IEEE Conference on Automation Science and Engineering (CASE)*, p. 1099-1105.

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[C19] Talke, K, Drotman, D, Stroumtsos, N, de Oliveira, M, **Bewley, T** (2019) Design and parameter optimization of a 3-PSR parallel mechanism for replicating wave and boat motion *International Conference on Robotics and Automation (ICRA)*, p. 7955–7961.

[C20] Duenas, J, Nezampasandarbabi, F, **Bewley, T** (2019) A systems engineering Persistence Of Vision teaching module integrating coordinated sensing, actuation, multithreaded computation, custom PCB design, and inductive power transfer. *AIAA Scitech Forum*, AIAA 2019-0063, p. 1-9.

[**A3**] **Bewley, T** Autonomous balloon swarms for persistent, in situ, real-time measurement of hurricanes, and a Drunken Sailor perspective and Spontaneously Singular Control approach for Lagrangian particles in turbulence. *GALCIT Colloquium, Caltech.*

[**A4**] **Bewley, T**, Luchini, P, Meneghello, G (2019) A new Drunken Sailor perspective and Spontaneously Singular Control approach for Lagrangian particles (buoyancy-controlled balloons) in highly stratified turbulence, *APS Division of Fluid Dynamics Meeting Abstracts.*

[**J10**] Alimo, R, Beyhaghi, P, **Bewley, T** (2020). Delaunay-based derivative-free optimization via global surrogates. Part III: nonconvex constraints. *Journal of Global Optimization* **77**, p. 743-776.

[**J11**] Beyhaghi, P, Alimo, R, **Bewley, T** (2020) A derivative-free optimization algorithm for the efficient minimization of functions obtained via statistical averaging. *Computational Optimization and Applications*, **76** (1), p. 1-31.

[**C21**] Beyhaghi, P, Alimo, S, Zhao, M, **Bewley, T**. (2020). A Delaunay-based method for optimizing infinite time averages of numerical discretizations of ergodic systems. *AIAA Scitech Forum*, AIAA 2020-0903, p. 1-12.

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[**J12**] Alimo, R, Cavaglieri, D, Beyhaghi, P, **Bewley, T** (2021) Design of IMEXRK time integration schemes via Delaunay-based derivative-free optimization with nonconvex constraints and grid-based acceleration. *Journal of Global Optimization* **79** (3), p. 567-591.

[**C25**] Claudet, T, **Bewley, T**, Alimo, S (2021) Stabilization of a Planetary-Explorer Balloon-Payload System using Tensegrity. *AIAA Scitech Forum*, AIAA 2021-0741, p. 1-16.

[**C26**] Strawson, J, Cao, P, Tran, D, **Bewley, T**, Kuester, F (2021) Monocoque Multirotor Airframe Design with Rotor Orientations Optimized for Direct 6-DoF UAV Flight Control. *AIAA Aviation Forum*, AIAA 2021-2431, p. 1-11.

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[C28] Cao, P, Strawson, J, **Bewley, T**, Kuester, F (2021) Decoupled translational and rotational flight control designs of canted-rotor hexacopters. *AIAA Scitech Forum*, AIAA 2021-1058, p. 1-13.

[C29] Cao, P, Strawson, J, Zhu, X, Zhou, E, Lazar, C, Meyer, D, Zheng, Z, **Bewley, T**, Kuester, F (2022) BeagleRover: An Open-Source 3D-Printable Robotic Platform for Engineering Education and Research. *AIAA Scitech Forum*, AIAA 2022-1914, p. 1-16.

Submitted and (as of fall 2021) still under review:

[**S1**] **Bewley, T**, Luchini, P A new method for approximating proportional representation in multi-seat elections based on range or approval voting. Submitted to *Social Choice and Welfare*. (12 pages)

[**S2**] **Bewley, T** Exponential stabilization of a variable-length pendulum with nonlinear feedback and a curious caveat. Submitted to *Automatica*. (9 pages)

[**S3**] **Bewley, T** A quaternion-based formulation for the dynamics of tensegrity structures with embedded solid bodies, including structures that are tensionable under load. Submitted to *Computer Methods in Applied Mechanics and Engineering*. (15 pages)

[**S4**] **Bewley, T** Stabilization of low-altitude balloon systems, Part 1: rigging with a single taut ground tether, analyzed as a variable-length pendulum. Submitted to *AIAA Journal of Guidance, Control, and Dynamics*.

[**S5**] **Bewley, T** Stabilization of low-altitude balloon systems, Part 2: riggings with multiple taut ground tethers, analyzed as tensegrity systems. Submitted to *AIAA Journal of Guidance, Control, and Dynamics*.

[**S6**] **Bewley, T**, Mashayek, A, Cavaglieri, D, Luchini, P Tweed and wireframe: accelerated relaxation algorithms for multigrid solution of elliptic PDEs on stretched structured grids, Submitted to *Journal of Computational Physics*. (25 pages)

[**S7**] Talke, K, Birchmore, F, **Bewley, T** Autonomous Hanging Tether Management and Experimentation for an Unmanned Air - Surface Vehicle Team. Submitted to *Journal of Field Robotics*. (25 pages)

[S8] **Bewley, T**, Ziane, M A general method for direct elementary construction of compact C^∞ sigmoid functions. Submitted to *Real Analysis Exchange*. (5 pages)

Under active Preparation:

[**P1**] Beyhaghi, P, Alimo, S, **Bewley, T** Uncertainty Quantification of the time-averaged statistics derived from a numerical simulation of a turbulent flow. Under preparation. (21 pages)

[**P2**] Talke, K, Friend, J, **Bewley, T** On dynamics and numerical simulation of a three-dimensional elastic string pendulum. Under preparation. (43 pages)

[**P3**] Luchini, P, **Bewley, T** A new Drunken Sailor perspective for modeling the motion of Lagrangian particles (buoyancy-controlled balloons) in highly stratified turbulence. Under preparation.

[**P4**] Luchini, P, **Bewley, T** A Spontaneously Singular coordination approach for buoyancy-controlled balloons in stratified turbulence. Under preparation.

[**P5**] **Bewley, T** Numerical Renaissance: simulation, optimization, and control, 2nd edition. Under preparation.

[**P6**] **Bewley, T** Renaissance Robotics: embedding multithreaded real-time feedback into mobile robots and cyber-physical systems. Under preparation.

USPTO Patents issued

US Patent # 10611019 (2020), 9902058 (2018), 9757855 (2017), 9020639 (2015): Multimodal dynamic robotic systems

US Patent # 10189342 (2019): Ball-balancing robot and drive assembly therefor

US Patent # 8083013 (2011): Multimodal agile robots

Note that I am the first author on all of these patents, which are each assigned to the UC Regents.

Supporting figures

In an effort to make just a few of the projects discussed above a bit more visual, a few related images are provided below; the reader is encouraged to follow various links provided above for substantial additional information and visualizations.

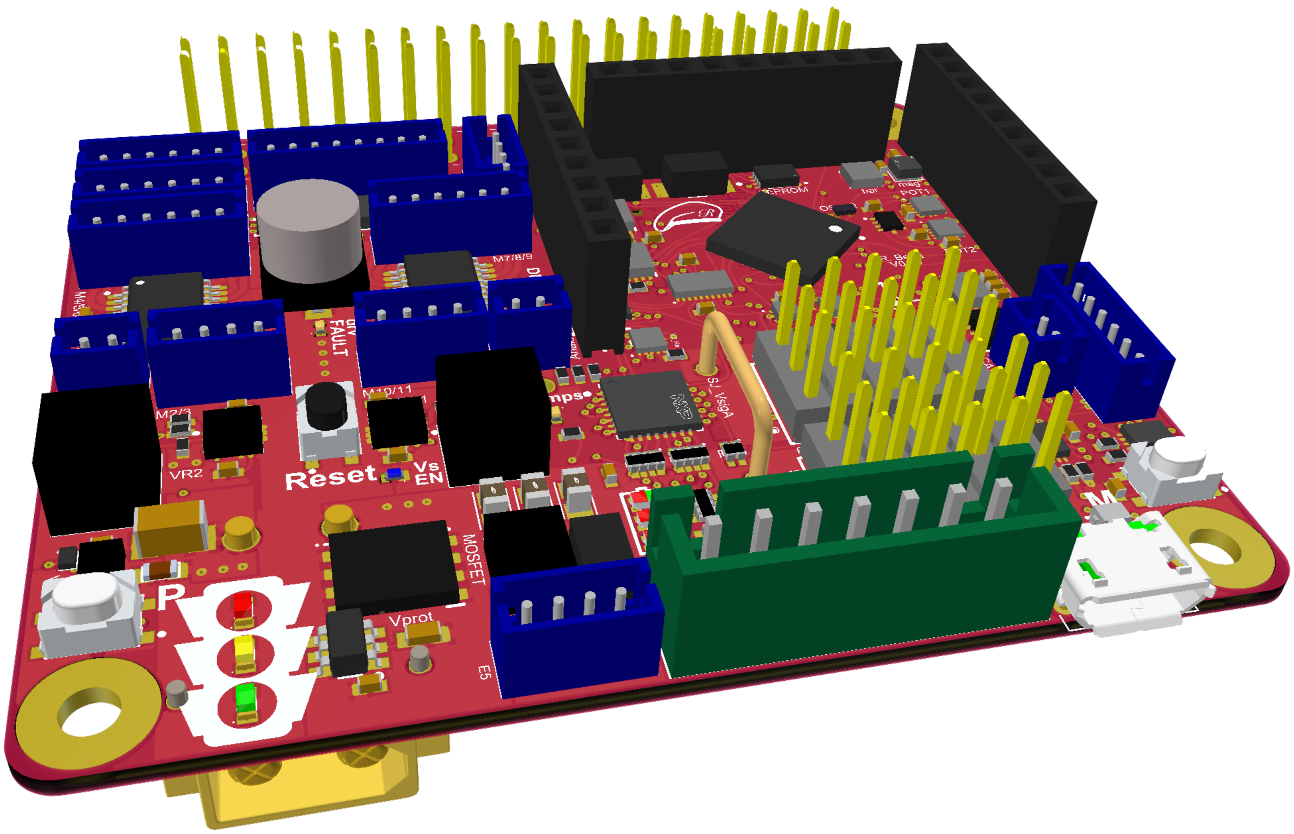

Figure 1: (above) The Raspberry Beret, and (below) a frame from a movie (available here) illustrating its integration with multiple Green Berets over RS485, in order to drive a large number of slave devices. See §1.1; full datasheet available as chapter 5 of RR [P6].

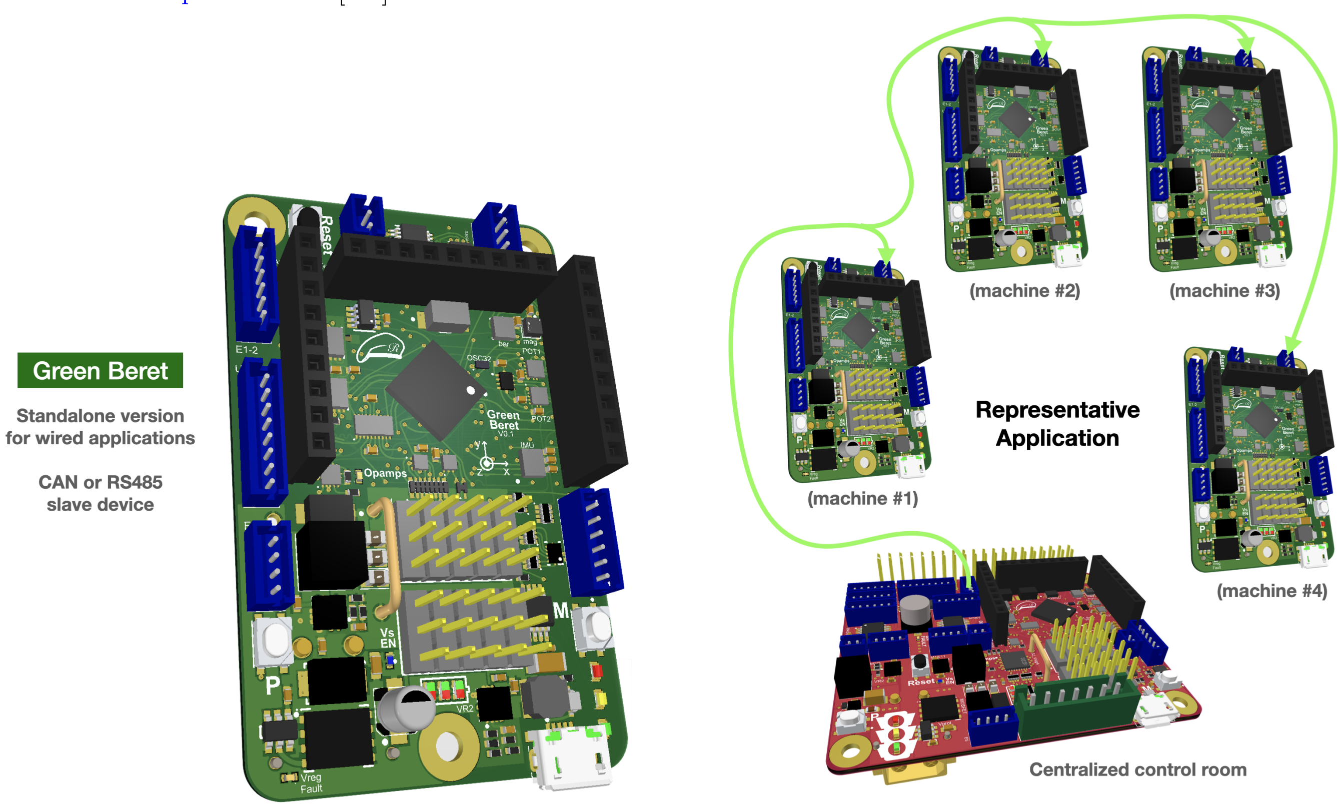

Figure 2: MiP display at the entrance hall to the UCSD Jacobs School of Engineering, illustrating (in the center) three previous-generation eduMiPs, flanked by several variants of the consumer MiP that we worked with WowWee to bring to the mass market, selling (in total) millions of units (see §1.2).

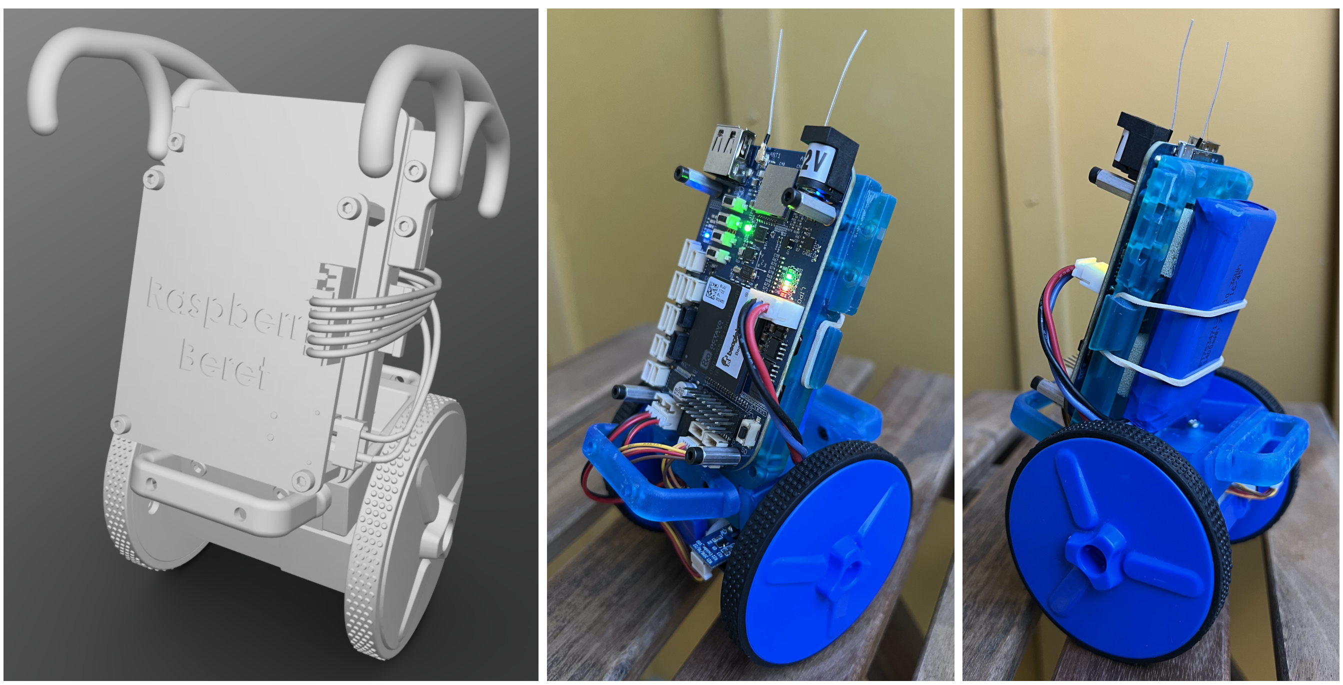

Figure 3: The next-generation myMiP educational robotics kit (see §1.2). (left) CAD, outfitted with a Raspberry Pi and the new Raspberry Beret (see Figure 1 and §1.1), (center, right) front and back images of a 3D-printed prototype outfitted with a Beaglebone Blue (also developed by our lab, working closely with Beagleboard.org).

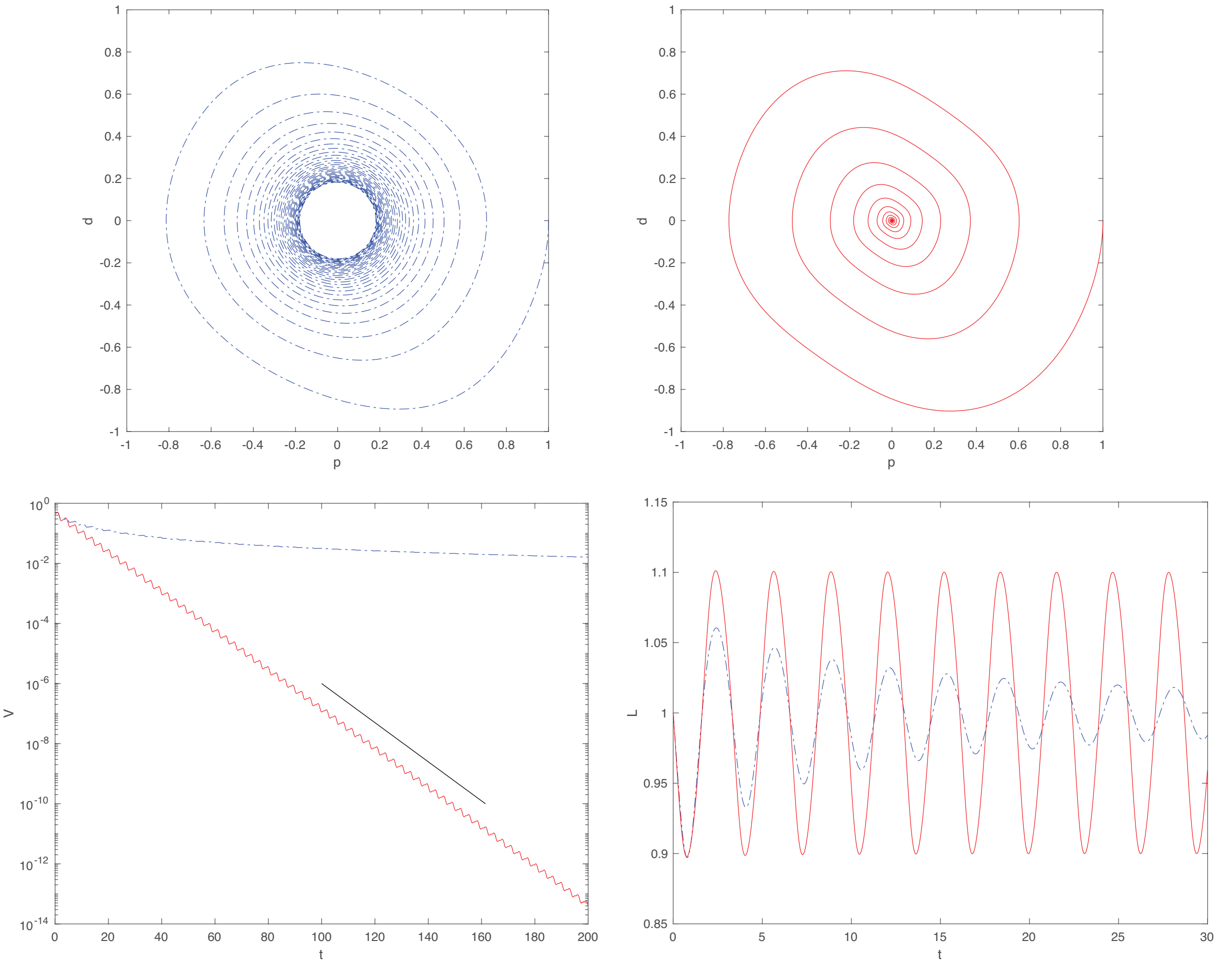

Figure 4: Stabilization of a singly-tethered balloon system (see §3.1 and [**S2**]). An animation of such a result is here.

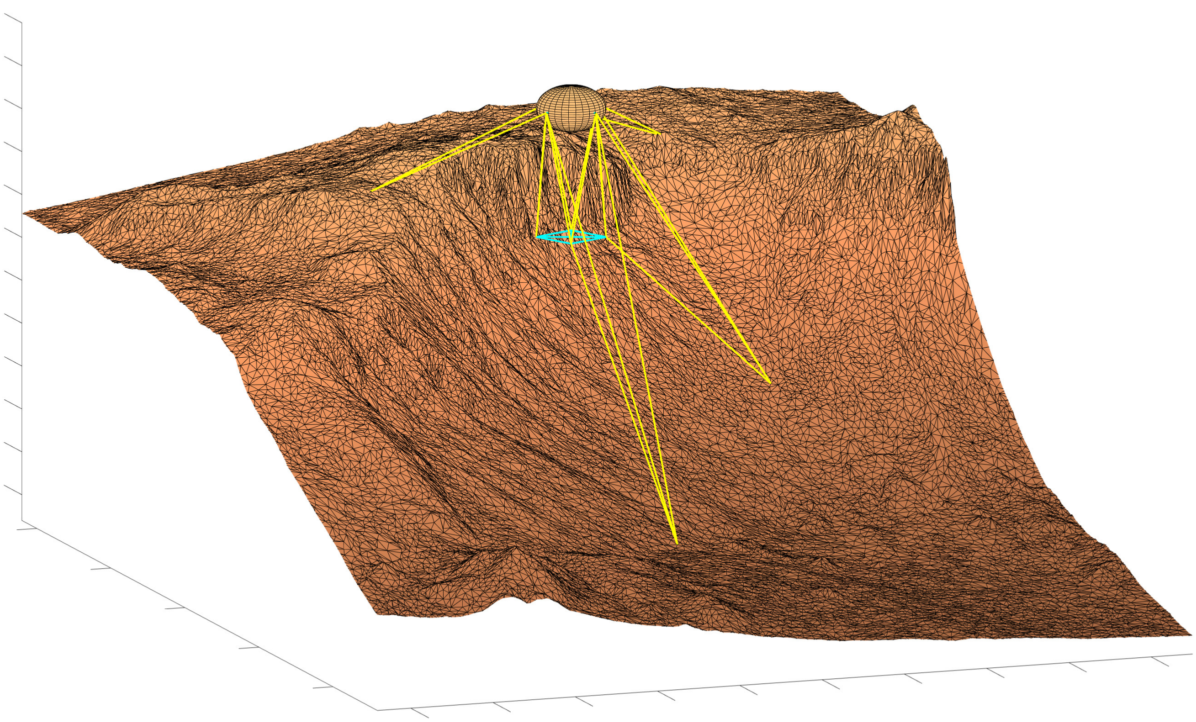

Figure 5: A potential stabilized deployment scenario for a remote observation platform suspended over a cliff on Mars from a hydrogen-filled balloon tethered to fixed or mobile ground attachment points (see §3.2 and [**S5**]).

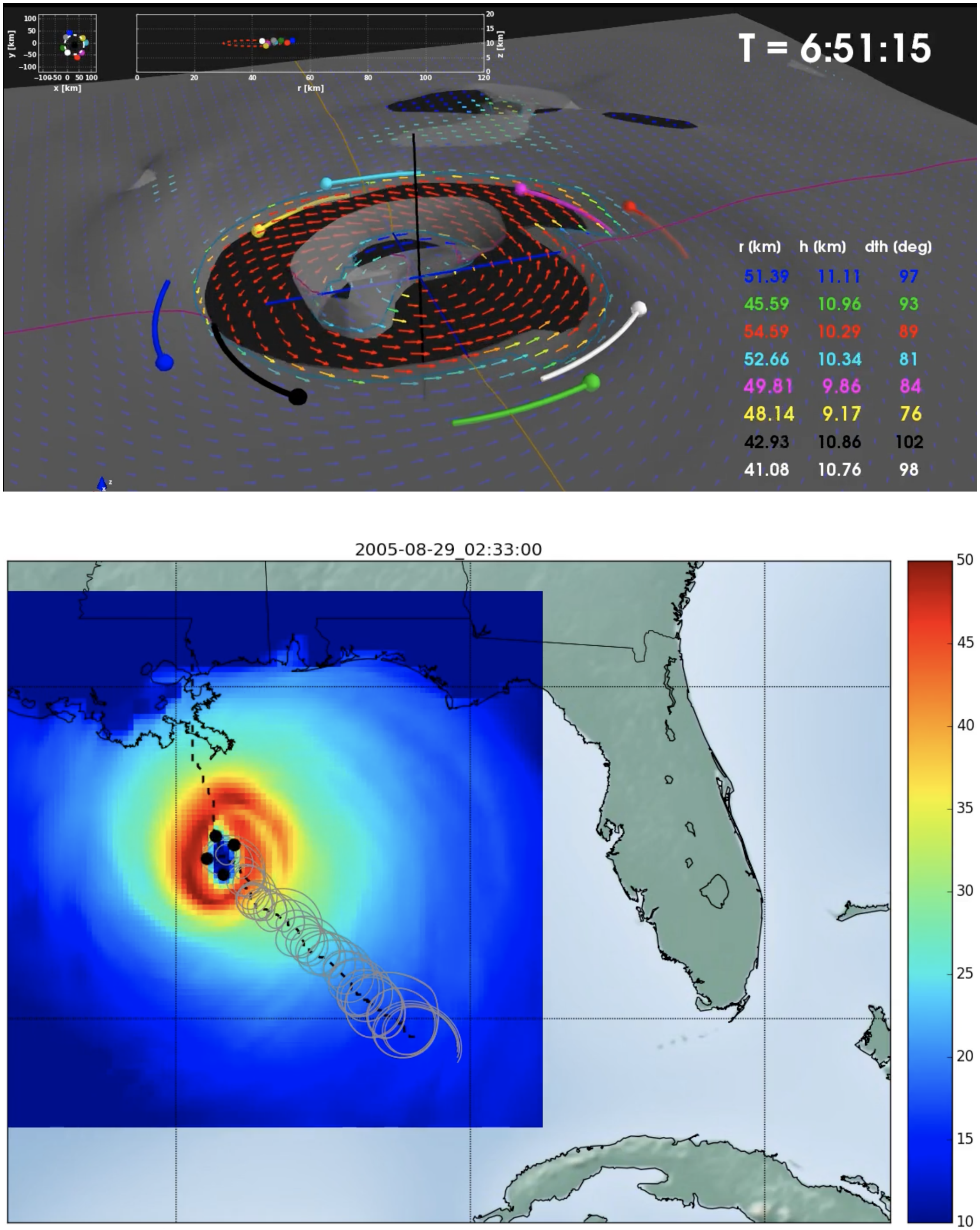

Figure 6: Representative frames from two animations, available **here** and **here**, depicting the problem of coordinating the motion of sensor balloons in hurricanes (see §3.3 and [**J4**])

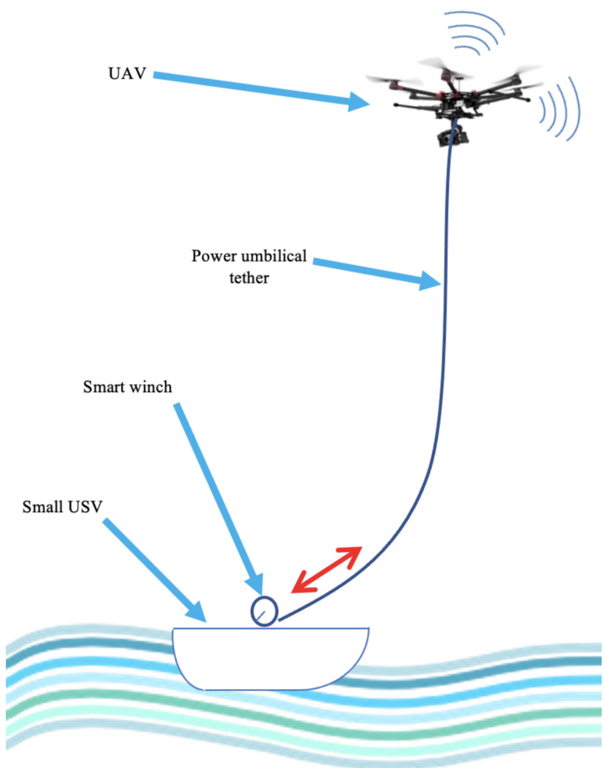

Figure 7: (above) A coordinated UAV/USV team. (below) A test of our active tether management strategy, using a 3-PSR parallel mechanism for replicating wave and boat motion See §5, [S7], and [C19].