Lessons Learned from a Control Systems Way of Life

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As a control engineer (and proud of it!), I know that controlling through transition—the transient response—is the most difficult part of a control problem but also the part where you learn the most. So, I would like to reflect on the "lessons learned" during the transitions and uncertainties that have occurred during my career and hope they help some of you think about your future.

My life breaks down nicely into roughly 20-year segments. My first 20 were dedicated to getting a driver's license, getting out of high school, and getting into the University of Florida. The next 20 were dedicated to getting out of college, getting married, raising a family, and working in aerospace and academia. The next 20 were dedicated to enjoying my family, except when my children got their driver's licenses, and working in the automotive industry, retiring when I turned 60.

I am now 67 years old, so I am seven plus years into my next 20 year segment (I hope)! I am doing something different from the prior 60 years because I believe that age is a state of mind and that learning totally new subjects makes life exciting and youthful. An education in control systems allows one to tackle almost anything (isn't life just a near-optimal nonlinear, stochastic control problem?!).

My working engineering career started in 1960 when I became a co-op student at the Army Ballistic Missile Agency in Huntsville, Alabama; later in the year it became the NASA Marshall Space Flight Center. I was assigned to the group that was struggling with the problem of controlling rockets with a new technology: the digital computer. And that leads to the first lesson.

LESSON NUMBER ONE: LUCK HAPPENS; TAKE ADVANTAGE OF IT!

At the time, we did not realize that the computer would change the world; to us it just represented a nasty engineering problem. Another piece of luck also occurred at that time: I met my wife of 45 years, Linda; having a great life partner sure makes life easier!

LESSON NUMBER TWO: EARLY IN YOUR CAREER, ONLY WORK WHERE YOU ARE CHALLENGED

If you are a recent graduate, in some sense you are like a newborn child ready to apply your recently acquired control system principles to the real world; the more difficult the challenge today, the better you will be equipped for an uncertain tomorrow, which leads to the next lesson.

LESSON NUMBER THREE: THE ONE THING ABOUT "TOMORROW" IS THAT YOU CAN'T PREDICT IT

Do you have some "factoids" from your university education that you know you will never forget? One that I remember from my freshman year is: "The only thing that doesn't change is change itself." Of course, "transition" and "transient" are words representing changing conditions.

NASA-Huntsville in the early 1960s was an exciting place. When I started, I was a second semester sophomore in engineering. The head of our group was Rudolf Hoelker, who was a member of Werner von Braun's original Peenemunde team and played a major role in developing the V2 guidance system. When I started, he gave me a workbook that required learning the orbital equations, performing Runge-Kutta numerical integration "by hand," and the delta-V guidance equations so that I would understand the basics.

I essentially worked for Bill Miner and Bob Silber, who were using the calculus of variations to develop the guidance laws for the Saturn I vehicle. I thus became a control engineer by doing optimal control as a 19-year-old sophomore! At that time (1960–1964), we had access to the best computers in the world. Within our workgroup, we moved rapidly from the IBM 690 to the 1620, and from assembly language to FORTRAN (what a blessing!), and even FORMAC, a formula manipulation language, which helped us develop higher order derivatives of the guidance equations. At the computer center, we moved from the vacuum tube IBM 709 to the solid-state 7090. Circa 1963, with the 1620, 7090, FORTRAN, and FORMAC, as far as I was concerned, we moved so fast to these new tools that little more was required in the computing world!

Bob Silber was a mathematical genius who loved to teach. He was always wrestling with a tough rocket guidance problem, and his way of dealing with it was to "lecture." He would say to me "Got a minute?" and then give me a lecture on the status of his solution; I learned a lot (even though I typically only understood half of what he was saying!). Our bible was Gilbert

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A. Bliss's *Lectures on the Calculus of Variations*. The saying among the undergrad co-ops was "ignorance is Bliss" because we were all struggling with the theory (Lesson 2).

Other great memories from the early 1960s NASA were "overnighters" at the computer center, contractor meetings, and test firings of the Saturn I and V boosters. As a co-op, you were willing to work any kind of overtime (which was not the case with "real" employees). There were many rocket launches at Cape Canaveral, and these required frequent, near real-time trajectory calculations as new weather data came in. This occurrence typically required all-night duty, with overtime pay, at the computer center; it was almost like a party.

NASA gave many contracts in support of the Apollo Program. Our group supervised several contracts dealing with the emerging optimal control theory and coordinated meetings involving all of the contractors. It was through these projects that I met Henry Kelley, Sam Pines, and Bob Kopp, and later when the group moved to the new NASA Electronics Research Center in Cambridge, Art Bryson, Dick Battin, Jason Speyer, and David Jacobson, among others. Those were great meetings, especially for a student. Everyone was struggling with both the theory and computational techniques, while applying both to real-life problems.

Finally, for pure excitement, we would get notice during the day that a rocket test would be taking place after work. In those days, we could get pretty close to the test stand. It was a mind-blowing experience: the exhaust fire, the rumbling noise, and the development of a man-made cloud from the vaporization of the water cooling the exhaust deflection shield.

When I interviewed for jobs after my B.S. degree, NASA said that if I would stay in Huntsville, they would send me to get my M.S. degree after a year of work. During that year, Lesson Number One ("Luck") came into play again: a consultant to our group at NASA, Byron Tapley, convinced my boss that NASA should send me to the University of Texas (UT) for my master's degree. I was at UT from 1964 to 1968.

UT was an exciting place in those days as well, and we had a great group of graduate students and professors interested in controls and space research; a real "brown bagger" atmosphere. My M.S. and Ph.D. theses were concerned with optimal control of low-thrust space trajectories, and techniques associated with their computation. Dr. Tapley built a tremendous group in space research, and on February 1, 2008, we had a big celebration in Austin celebrating his 75th birthday and 50-year anniversary teaching at UT; he's still going strong!

When I received my Ph.D., Lesson Number One came into play again: a member of my dissertation committee, Lyle Clark, recommended me to the University of Michigan, where he had once been a faculty member. To be truthful, I viewed the interview at Michigan as a rehearsal for my "real interviews" at other universities closer to home.

To say the least, I was impressed with Michigan and accepted their offer. We had a great group at Michigan: Bob Howe, Larry Fogarty, Harm Buning, Don Greenwood, Bill Root, Elmer Gilbert, Fred Beutler, Larry Rauch, Harris McClamroch, Ty Duncan, among others. I loved teaching at Michigan, but I always tried to have some consulting activity because it usually led me to problems that had a good blend of theory and application. In 1968, I spent part of the summer consulting at Northrop-Huntsville, and they were analyzing a problem that occurred on one of the Saturn-Apollo flights; an engine-out condition resulted in the thrust vector control hitting the control limits. This is how I got into the area of singular optimal control.

In the early 1970s, the bottom fell out of the aerospace industry, so I looked for some other areas to obtain funded research. Those of us in controls at Michigan were viewed as good partners for other research areas because we were "comfortable" with optimization and computational methods, as well as dynamic models, which were coming into vogue in economics, bioengineering, and water resources. Several of us in the controls group worked with others at the university in applying our techniques to their problems with good success. My two major areas were in biomedical (the control of anticoagulant drugs) with Peter Abbrecht and water resources (computational techniques for Lake Michigan and Saginaw Bay eutrophication models) with Ray Canale.

An education in control systems allows one to tackle almost anything.

Harm Buning had spent a sabbatical in Houston in the early 1960s and taught courses in orbital mechanics to many of the astronauts. As the Shuttle Program was developing, Harm got a call from Houston to put a Michigan team together to come teach a short course on subjects pertinent for a "rocket airplane." A group of us then went to Houston and presented lectures on various subjects. After the course was over, NASA-Houston asked Harm if one of the team could spend the summer in Houston; as the only assistant professor on the team, I was elected, and Lesson One came into play again! I then consulted with Houston until I went to Ford at the end of 1979. To say the least, it was fascinating to watch the Space Shuttle Program unfold: from the original two shuttles (NASA and Air Force) with a reusable booster to the final solid rocket-assisted boosted Orbiter.

At University of Michigan in 1971; Apollo 15 crew getting ready to fly back to Houston after receiving honorary degrees. From left: Bob Howe, Dave Scott, Harm Buning, Jim Irwin, Bill Powers, and Al Worden.

In Moscow, May 1976, on National Academy of Sciences US-USSR Exchange Program. With Moscow Aviation Institute professors Yuri Plotnikov, Igor Pegov, and their families. Prof. Plotnikov and Prof. Pegov spent time earlier at the University of Michigan as part of the same exchange program.

I was associated with the Mission Planning and Analysis Division at NASA with John Mayer, Ivan Johnson, Hank Sullivan, Bobby Uzell, and Ron Berry, among others. After it was decided that there would be only one Shuttle program, a key technical question was: How do you fly the Shuttle during re-entry to maximize cross range while minimizing the Shuttle weight, and how do you compute the optimal trajectory? I found a way to formulate the problem as an optimal minimax problem, which allowed us to employ slightly modified state-variable inequality-constraint accelerated gradient methods.

Later at NASA, our group became interested in microprocessors and microcomputers. I was impressed; I felt that microcomputers would change the world! So, back at Michigan, I started to get "hardware" oriented for the first time in my career. We had a group that first played with the 6502-based Kim computer and then the 6502-based PET and Apple I computers. Many of us would gather at Newman Computer Exchange in Ann Arbor on Wednesday afternoons to exchange facts/rumors about the rapidly changing area. I even developed my own word processor program using peek and poke commands from a Basic program developed by a "kid" named Gates!

In 1975 I spent my sabbatical leave at the Technical University of Munich with Roland Bulirsch and the DFVLR in Oberpfaffenhofen with Jurgen Ackermann, Klaus Well, and Willy Kortum, among others. I emphasized learning about stiff integrators, which were playing an increasingly important role in all kinds of simulation, especially environmental systems, where without stiffness, nutrients would "go negative," as well as in applied filtering techniques. When I returned to Michigan, I taught the first applied Kalman filtering course at Michigan; of course, Bill Root and Fred Beutler had already been teaching the first courses in stochastic processes for our control students. In 1976, I participated in a month-long National Academy of Sciences exchange program with visits to control institutes and universities in the USSR, Czechoslovakia, and Yugoslavia. One of the great things about control engineering is the relatively long history, since World War II, of tremendous international interactions.

During the mid 1970s, I had graduate students from the automotive industry struggling with putting computers on cars, so Lesson Number One came into play again and I got involved. One of my Ph.D. students, Al Dohner, and I taught a summer short course at the University of Michigan in 1979 titled "Optimal Control with Application to Automotive Engine Control." Several students in the course were Ford employees, and some of them encouraged me to consider working at Ford.

In December 1979, I started the next 20-year segment, leaving an exciting, comfortable, tenured professorship for the automotive industry, which was on the verge of its worst recession in modern times; I had not learned Lesson Number Three, an unpredictable tomorrow, at that time!

But Lessons One and Two came back into play: I was challenged and the recession was actually lucky for our industry because it made us change. I must say that those 20 years were the most fun and interesting because they involved a very nice blend of technology and business.

When I went to Ford, it was as exciting as the 1960s in space because we were totally computerizing the automobile. Everything started with engine controls; by necessity this work had to meet the new, tight emissions and fuel economy standards, and had to be "tamper proof" so that the vehicle's emissions could not be changed. From 1980 to 1986, I was manager of the Ford Research Control

Systems Department. We had a great group, and we were involved in trying to computerize every subsystem in the automobile. Many of our efforts got into production, and that is what is great about the auto industry: you can see your efforts in production in a reasonable amount of time.

Some our best control systems work never got into production, for example, active suspension control systems, where Davor Hrovat acted as one of our internal consultants. The reason was that the system added considerable cost and weight to the vehicle, and "the value" could not be easily demonstrated to the "average" customer at the time, although some future generations of active suspensions combined with better actuators and additional functionality may change this value equation. A similar example was rear-wheel steering, where to demonstrate the benefit to a customer you essentially had to create an artificial experience, such as a tight turn on a cul-de-sac.

Speaking of Davor, he is also proud to be a control engineer, and he has demonstrated the breadth of control engineering to almost any problem. Boeing approached me in 1999 and asked if we would loan them Davor to be part of the 737 Study Team to analyze some problems discovered in the field. They wanted someone who was not associated with aerospace (most of the other members of the team had aerospace backgrounds), that is, "fresh eyes." (I'm a big believer in "fresh eye reviews.") Davor went to Seattle for a little over a year and made significant contributions to the study, including a unique sensor solution to measure internal spool position of critically important rudder control valves.

In 1987, I was transferred to the operations in Ford, and, in particular, to head up a new organization called Product and Manufacturing Systems, essentially all technical computing in North American automotive operations. It was my first time out of a research-oriented environment, and it was my first major experience blending the financial part of business with technology, for example, making large purchase agreements with computer and telecommunication companies. At the time, IBM and DEC were the two largest computer companies, and HP was essentially a scientific instrument company with some computing capability at the lower end. The "hottest" areas at the time were open systems and CAE workstations. In some sense, HP embraced both open systems and CAE workstations (by buying Apollo Computer Company); in addition, because of HP's capability in scientific instrumentation, they were also very good in networking. Today, DEC is gone and in fact is essentially part of HP (after HP's purchase of Compaq, which purchased DEC); Lesson Number 3 again (can't predict tomorrow), namely, who in 1988 would have predicted that Compaq would buy DEC in 1998?!

In 1989, I was transferred to another operational position: program manager for Specialty Car Programs, which included the Thunderbird, Cougar, and Mark VII and VIII. I probably learned more on this job than any other in my life. I had to interact with every part of the company and the suppliers. We were developing the Lincoln Mark VIII, which was the highest tech car Ford had produced up to that time: all-new, all-aluminum four-valve V8 engine, adaptive suspension system, new lightweight materials (for example, "soft chrome" grill), and voice-integrated phone with a pillar-mounted microphone (new in 1992). The program involved a strong dose of project management, and it taught me the "magic" of many project management techniques. One in particular is the formal use of a "Risks and Opportunities List (R&Os)." We had to decrease the weight of the vehicle, and, initially, there were very few ideas for weight reduction. We then required each team to bring in for review each week a list of R&Os, and the list had to have at least one "O". Over time, with team peer pressure, we developed many opportunities that ended up in production. R&Os is a simple process that can be very effective in a team environment. After developing the Mark VIII "EPs" (evaluation or engineering prototypes), I was appointed head of the Ford Research Laboratory in 1991.

In 1994, Ford reorganized the company and called it Ford 2000, which involved an integrated global organization. I was asked to head up the new Information Technology (IT) organization for 18 months, while retaining my research position, since I had been in a major IT position in the 1980s. Although many media assessments of Ford 2000 have been negative, I think the globalization of IT worked. In fact, in my opinion, in global organizations, anything ruled by Newton's laws or technology ought to be globalized, while sales and marketing should be localized. I thoroughly enjoyed this job, too, with direct reports in the United States, the United Kingdom, and Germany, and developing Ford's first Internet site (Ford.com) in July 1995.

In February 1996, I became vice president of worldwide research for Ford. This job required a major blending of global governments, business, and technology, again a very interesting learning experience. Two examples come to mind. Vice President Gore was a strong proponent of cleaner, more fuel efficient vehicles, and he personally sponsored annual technical conferences. I had the pleasure of working with him, his staff, and others from the auto industry to develop a consensus position on the future of diesel-type engines, which many had viewed negatively up to that point; I was fortunate enough to represent the auto industry in a joint speech with Vice President Gore announcing our consensus views.

The second example had to do with Ford's efforts in China. I, along with others in Research, had been helping our company with their initial efforts,

In anteroom prior to joint presentation on advanced engine technologies, including diesel engines. From left: Vice President Gore, Ken Oscar (acting assistant secretary, Research, Development, and Acquisition, United States Army), Bill Powers, Senator Carl Levin, and Jack Gibbons (science advisor to President Clinton).

With "fellow control engineers" at the 1999 Triennial IFAC conference in Beijing; from left: Bill Powers, Manfred Thoma, Karl Astrom, Petar Kokotovic, Song Jian, Yu-Chi Ho, and Masayoshi Tomizuka.

including sponsored R&D with Chinese universities. During this period, I met Dr. Song Jian, who was strongly involved with Chinese government affairs in engineering, science, technology, and the environment. We discovered that we were "fellow control engineers," and to this day, since we are both in retirement, we refer to each other as "fellow control engineer." When you meet a fellow control engineer, you can take certain things for granted: you both understand constraints, math models, first principles, performance indices, and process and measurement noise, among others. In other words, you know how each other thinks about things, which definitely aids communication.

I retired in December 2000, and since then I have been concerned with energy issues in general, working with the Department of Energy, Sandia National Laboratories, and the National Academy of Engineering. I am amazed at how little the media, and, thus, the general populace, understands about the fundamentals of our total energy system, especially the role of nuclear and fossil fuels (~93% of our energy) and the "emerging renewables (solar and wind)" (less than 1% of our energy, but gets 99% of the press)! I have served on the National Academies Board on Energy and Environmental Systems for five years, and we recently developed a booklet titled "What You Need to Know About Energy" (available for download at www.nationalacademies.org/energy-booklet). The booklet was developed because many of us on the committee were continually surprised at how little many educated layman understood our national energy system and the near- and long-term possibilities for change. I strongly recommend the booklet (it's a quick read), especially the total energy input-output flow chart on p. 18.

Based upon my Ford experiences, as well as those at the "early NASA" and the universities of Florida, Texas, and Michigan, I have observed some further lessons that seem to be characteristic of outstanding work groups, organizations, and, more importantly, people who have had to be nimble with respect to change (which is no trouble for a control engineer who believes in transients and respects process noise).

LESSON NUMBER FOUR: BE CUSTOMER ORIENTED

It is easy to say you are customer oriented, but making it the true basis for decision making can be a struggle. No matter what you do in life, you will have customers. By viewing problems from the customer's perspective almost always gives not only new insights, but also the correct insights. Two of my favorite phrases in this regard are: "Surprise and delight the customer" (from Lew Veraldi, who was head of Ford's original Taurus program) and "The customer may not always be right, but the customer is the customer!" (from Ross Roberts, who was a longtime leader in sales and marketing at Ford).

LESSON NUMBER FIVE: PRACTICE CONTINUOUS IMPROVEMENT FOR THE DEVELOPMENT OF COMPETENCY

This is the least understood principle because many people interpret it to mean: "Don't Stretch." In some sense continuous improvement is in the eye of the beholder. Most of us would view Newton's development of his laws and the calculus as leapfrog; I certainly do. But, there was one person who viewed them as continuous improvement: Newton himself. One of his most famous quotes is: "If I have seen further than other men, it is because I have stood on the shoulders of giants."

LESSON NUMBER SIX: PRACTICE JUST-IN-TIME, OR MINIMIZE "DELAY"

Control engineers understand this principle because control theory shows that delay is typically a key destabilizer. We mainly hear about just-in-time with respect to manufacturing. I think it has much broader implications; namely, "quick feedback" in everything we do from inventories in plants to decision-making and authority levels in engineering.

LESSON NUMBER SEVEN: THINK SYSTEMS

To be a true systems thinker, the system must be more important than the component. It is interesting to note that all industries feel they have an insufficient number of "systems engineers." Part of the problem is that today's component was yesterday's system, and "systems problems" is in some sense the black hole for "hard problems." Good systems solutions almost always involve a solid goal with an interdisciplinary team that buys into the goal; like the well-understood U.S. goal of "going to the moon" supported by the total country and its strong interdisciplinary technical resources in the 1960s.

The lessons I have discussed so far are mainly associated with how to do work. I'd like to conclude with a few words about career development.

LESSON NUMBER EIGHT: BROADEN

A way to think about it is: "Grow the 'T'." As a young control engineer, you are an "I," that is, a control engineering specialist. Whatever you do, continue to "grow the "I" but also "grow the "T" by learning across, for example, learn about other technologies, business principles, how to learn, and the world.

LESSON NUMBER NINE: DEVELOP PERSONAL RELATIONSHIPS AND NETWORKS.

Treasure and nurture the personal relationships that you develop. Most of you have had e-mail and the internet during your education and early working career; use them to stay in touch with each other.

And, the final lesson.

LESSON NUMBER TEN: TAKE PERSONAL CONTROL AND DO SOMETHING EXTRA.

Some of you will go to work for medium- to large-sized companies. If you do, I recommend that you take one of the company sponsored courses on career development. There is one fact that stands out more than any other from such courses: you have more influence over your own career than you think you do.

I wish you the best as you "control" your way through the transients in your life. I have used my working career as the basis for the lessons learned, but all of the lessons pertain to nonworking life as well. I hope that when you are "old and gray and full of sleep," as the poet William Butler Yeats once wrote, that you can say that your goal in life was not the perfection of work alone but the perfection of a life.

AUTHOR INFORMATION

William F. Powers retired as vice president-research from Ford Motor Company on December 31, 2000; he had been with the company since 1979. During his career at Ford, he served as the first director of Product and Manufacturing Systems in North American Automotive Operations, program manager, Car Product Development Specialty Car Programs, where he was responsible for the Thunderbird, Cougar, and Mark VIII vehicles, and executive director of Information Technology. On February 1, 1996, he assumed the responsibilities of vice president-Research. He received his B.S. in aerospace engineering in 1963 from the University of Florida and his Ph.D. in engineering mechanics in 1968 from the University of Texas at Austin. At NASA Marshall Space Flight Center from 1960 to 1965, he was involved with the development of the Saturn Booster guidance system and Apollo mission analyses. He consulted on the Space Shuttle Program with the NASA Johnson Space Center during the period 1970–1979. From 1968 to 1980, he was a professor of Aerospace Engineering and Computer, Information and Control Engineering at the University of Michigan. Within IFAC, he organized and served as the first chair of the Automotive Control Technical Committee, and presented plenary lectures on automotive control at the 1993 and 1999 IFAC Triennial Congresses. He is a member of the National Academy of Engineering, a Fellow of the IEEE, the American Society of Mechanical Engineers, the International Federation of Automatic Control, and the Society of Automotive Engineers, and a foreign member of the Royal Swedish Academy of Engineering Sciences. He has received Distinguished Alumnus awards from the University of Florida (2001) and the University of Texas at Austin Engineering College (1993), the Control Practice Award from the American Automatic Control Council (2004), and the Nichols Medal from the International Federation of Automatic Control (2005). He and his wife, Linda, reside in Boca Raton and Ann Arbor and have two children (Stephen and Leigh) and four grandsons (Bryson, Landon, Colby, and Payton).