SAFETY, ECONOMY, RELIABILITY, AND REGULATORY POLICY FOR UNMANNED AIRCRAFT

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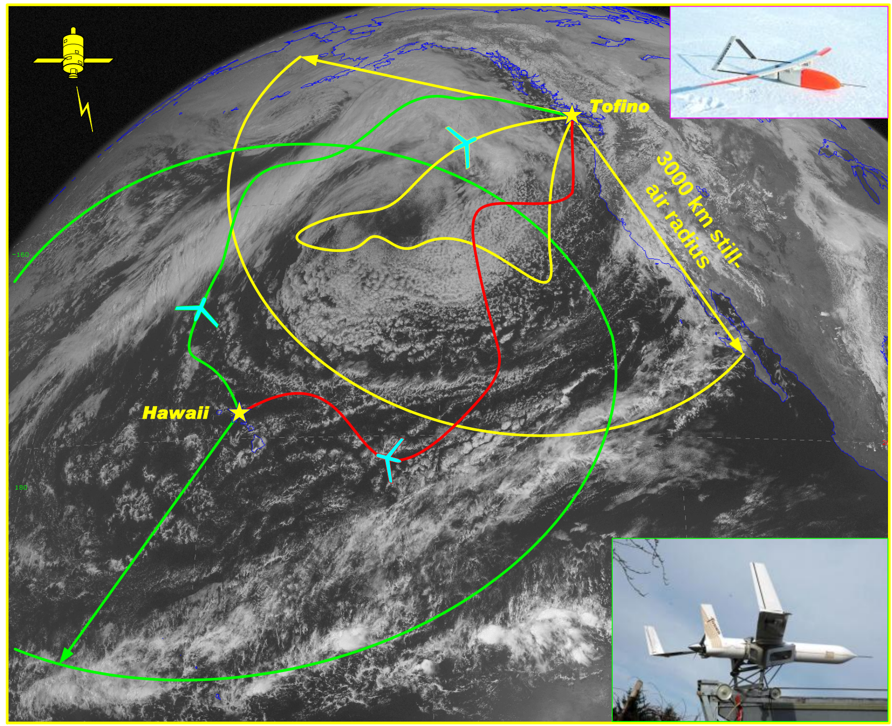


Figure 1. Offshore weather reconnaissance is one application in which robotic aircraft can excel. The payload involved is small, so the job can be done by aircraft much smaller and less expensive than would be necessary if a crew had to be carried onboard. Workload is sufficiently small that one operator can monitor many aircraft simultaneously. The market can be large enough to justify investment. Furthermore, the areas to be monitored have sparse air and surface traffic, so high safety can be achieved without high reliability (*cf.* Figure 2), and associated high costs for design and certification. Formative businesses in civil robotic aircraft are likely to depend on applications of this kind, but they can develop only if not precluded by proscriptive regulation.

Anyone with an interest in flying should spend a few moments at a web site called (I am not making this up) WillFlyForFood.cc. It includes, among much other useful information, detailed schedules of the threadbare pittances that aspiring pilots can expect to earn should they be so lucky as actually to sign on with the airlines. Regular viewers of the site may fear that we in the unmanned-aircraft business are dreaming up yet more ways to darken their often bleak earnings prospects, but I can assure them that the shoe is in fact firmly on the other foot. If only they didn't insist on being so ruthlessly cheap, life would be much easier for us struggling robotics entrepreneurs!

I make this point to contrast with comments that one hears from time to time suggesting that our biggest problem is regulation, or even a *lack* of regulation. A 2004 paper from the European Joint Aviation Authorities is not atypical in asserting the "recognised need for … regulations of civil Unmanned Air Vehicles", lack of which "… is seen as a major obstacle to further development of … UAV applications." (JAA 2004) I have variously led or been involved in quite a few ambitious trials of robotic aircraft in various jurisdictions around the world since 1995, and in my experience regulation, let alone lack of regulation, has not been much of a problem (*e.g.* Holland *et al* 2001; McGeer *et al*. 1999). It is unfortunately true that regulatory policy in the United States has grown into a formidable obstacle, but policy in Canada and Australia, for example, has been and remains quite capable of accommodating large-scale, long-term operations. Why, then, has the oft-discussed burgeoning future for robotic aircraft not already happened under these hospitable regimes? The answer, in a word, is economics.

I will begin this review with a brief discussion of economics, to indicate where unmanned aircraft are and are not likely to be competitive in the foreseeable future – in the best case, that is, which requires that prohibitive regulatory costs be avoided. I will then outline how applications having reasonable economics tend inherently to be safe, and suggest how wise regulatory policy can take advantage of synergy between economy and safety.

Observations on unmanned-aircraft economics

Unmanned aircraft can take a pilot out of harm's way, and this may be a compelling advantage in a few applications – but too few, in the civil realm, to attract much investment. A viable robotic-aircraft business will instead have to compete on price or performance in larger markets. On price, robotic aircraft have a long way to go.

Want to film from the air? Check out a stretch of road? Spray a field? Move some cargo? Pick up the phone; you can have an aircraft and its hungry crew ready at a nearby airport within a few hours. Costs range from around $100 per hour for a light single like a Cessna *Skyhawk*, up through $2000 or so for a *Citation*, and you can buy time in very small bites. In the unmanned-aircraft

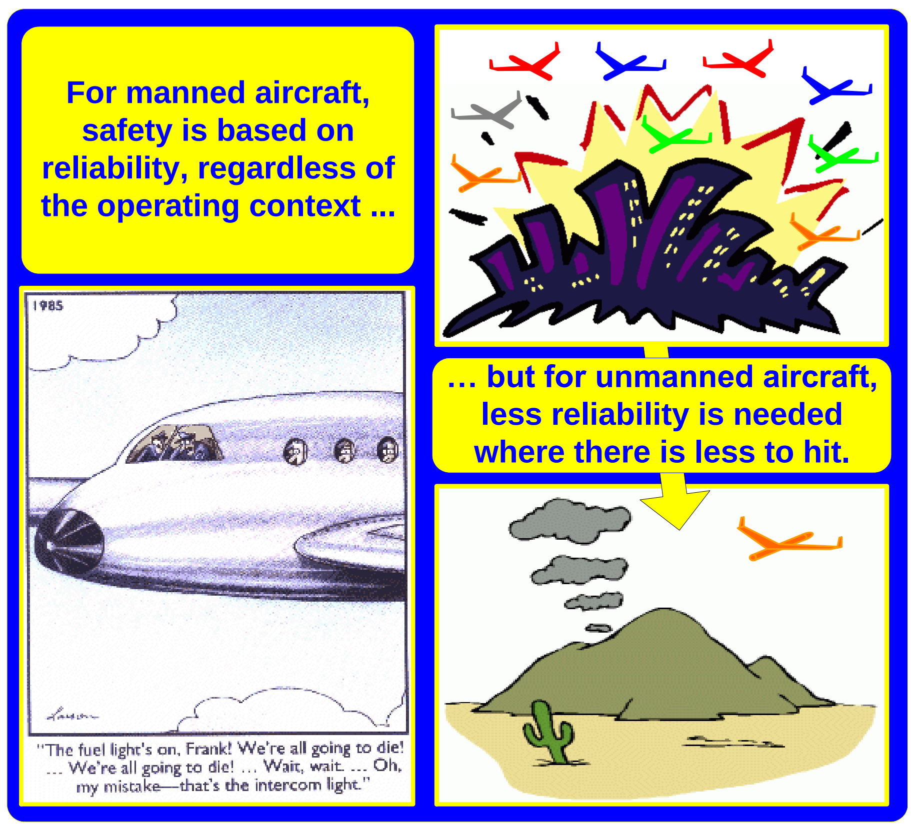
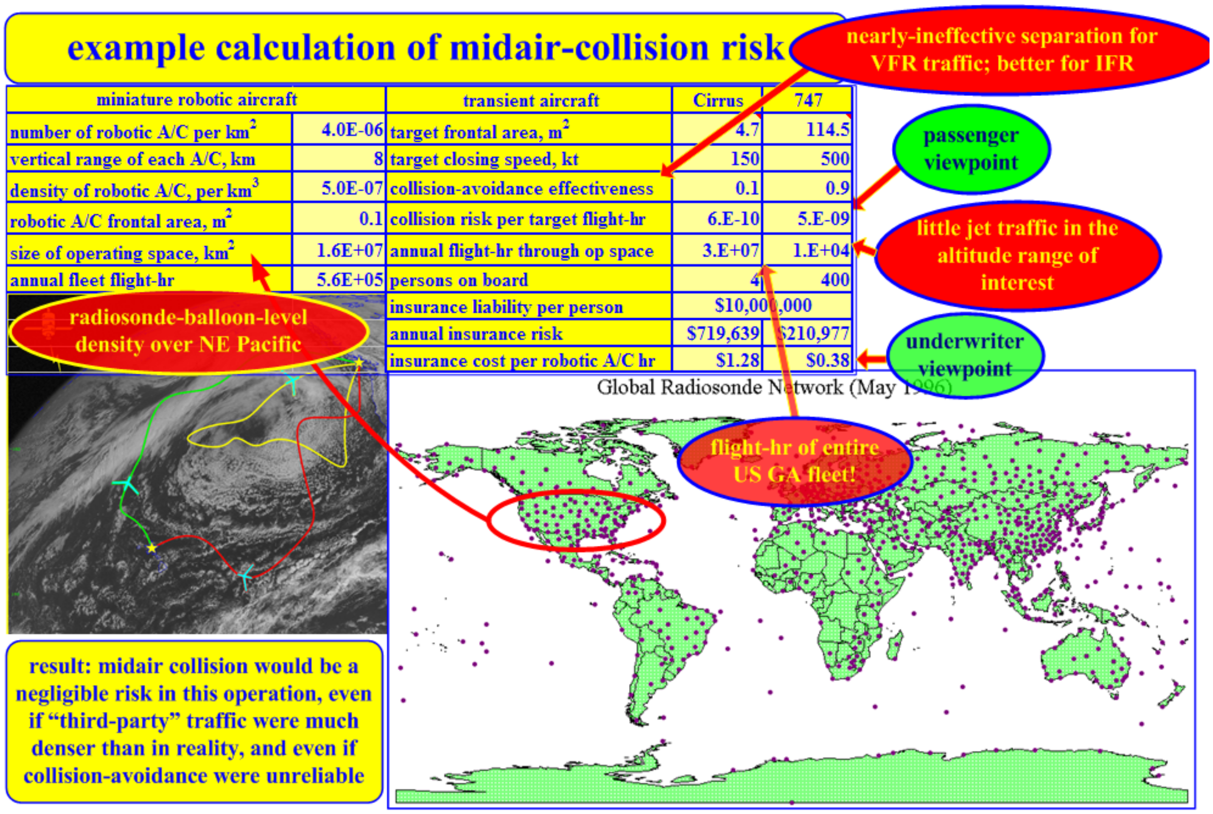


Figure 2. For manned aircraft, safety is inseparable from reliability. But for robotic aircraft the two are not so inextricably linked. Where air and surface traffic is sparse, risk can be low even with unreliable aircraft. Figure 3 and Figure 4 offer quantitative examples.



miniature robotic aircraft		transient aircraft	Cirrus	747
number of robotic A/C per km^2	4.0E-06	target frontal area, m^2	4.7	114.5
vertical range of each A/C, km	8	target closing speed, kt	150	500
density of robotic A/C, per km^3	5.0E-07	collision-avoidance effectiveness	0.1	0.9
robotic A/C frontal area, m^2	0.1	collision risk per target flight-hr	6.E-10	5.E-09
size of operating space, km^2	1.6E+07	annual flight-hr through op space	3.E+07	1.E+04
annual fleet flight-hr	5.6E+05	persons on board	4	400
		insurance liability per person	$10,000,000	
		annual insurance risk	$719,639	$210,977
		insurance cost per robotic A/C hr	$1.28	$0.38

Figure 3. As an example of risk assessment, suppose that in the weather-reconnaissance example of Figure 1, miniature aircraft were distributed over the Pacific with the same density as sounding balloons over the continental US (which are flown twice daily from the sites shown on the map). It turns out that – assuming pessimistically that efforts at separation were largely ineffective - a general-aviation aircraft flying through the operating space would have a collision probability less than 10^{-9} per flight hour. This is negligible in comparison to familiar risks such as those from birds, other manned aircraft, weather, *etc*. Further suppose that the density of "third-party" aircraft were likewise the same as that over the continental US – which is of course absurdly pessimistic for airspace over the ocean. Even then, the insurance premium necessary to cover the liability risk would be quite affordable, reflecting the very small hazards associated with the operation.

world, the same $2000 now buys taxpayers an hour of time on a tabletop-sized *Scaneagle* - and *Scaneagle* is at the low end of the market! Furthermore robotic-aircraft time is available for purchase only in seriously large blocks. Prefer to buy rather than rent? A *Scaneagle*, or even a short-range battery-powered *Raven*, costs more, and is a lot harder to get, than any number of nice low-time singles bought from the pages of *Trade-a-Plane*.

Of course production volume will bring costs down, but the price gap to be bridged is forbiddingly large. Hence the smart money seeks niches which avoid direct competition with manned aircraft. I look for a combination of features:

- **Remote areas.** The original idea for *Scaneagle*, for example, was to do video reconnaissance from fishing boats and other ships beyond reach of shore, for which the alternative is an expensive shipboard helicopter, or, for lack of space, no reconnaissance at all.
- **Scope for miniaturisation.** My favourite example is weather reconnaissance offshore (Figure 1), which calls for carrying a small payload over very large distances – *i.e*. tens of grams over many thousands of kilometers. A manned aircraft to do the job would be large and expensive, but a robotic aircraft can be tabletop-sized and relatively cheap. This is the *aerosonde* concept (see Holland *et al* 1991, McGeer & Vagners 1999), which has been explored in various trials including the first unmanned typhoon penetrations (2001, 2005) and the first unmanned Atlantic crossing (McGeer 1998). Miniaturisation also makes for unobtrusiveness, which is advantageous in, for example, wildlife monitoring and coastal patrol.
- **Parallel operation of multiple aircraft.** People involved in robotic aircraft operations tend to be more expensive than pilots: somehow there isn't much demand for WillSitAtAComputerConsoleInADarkRoomAndOperateUAVsForFood.cc. But a price advantage can still be gained where one person can supervise multiple aircraft. Weather reconnaissance falls into this category, as does geomagnetic survey, which involves the dull but exacting task of flying very straight parallel lines at low altitude for hours on end.

A further essential feature, or course, is that a niche be big enough to justify investing in a product to fill it. Applications for unmanned aircraft are unlikely to develop unless they can attract investment capital, and in my experience lack of capital has been by far the biggest obstacle to civil-applications development – much bigger than any technical or regulatory problem. The simple fact is that prospective markets are small and uncertain, which limits the sums that can be raised. A business plan can be built around investments of $5-10M, and money possibly attracted if sufficient effort is made. Substantially larger sums, however, are unlikely to be put in play, at least during the formative years of a civil business. (In this respect unmanned aircraft are at much the same stage as were manned aircraft up through the 1920s, or helicopters in the 1940s or 50s.)

Economic implications for regulatory policy

Any persistent entrepreneur who actually manages to scrape together some capital will have to put most of it into technical and business development; only a small portion will be available for regulatory compliance. But compliance for even a small manned aircraft, at least in the form of type certification, can these days cost many tens of millions of dollars.[1] Hence there might at first glance seem to be an insurmountable problem – and so there would be if regulations mandated anything like certification to manned-aircraft standards. Fortunately, however, that is not necessary to achieve safety, provided that the robotic aircraft in question are operated appropriately.

At this point one should consider the objective of aeronautical regulations. They are all about safety, and specifically the safety of three stakeholders:

[1] *e.g*. $70M reported for the Cirrus SR-20. See *Plane & Pilot*, December 2004.

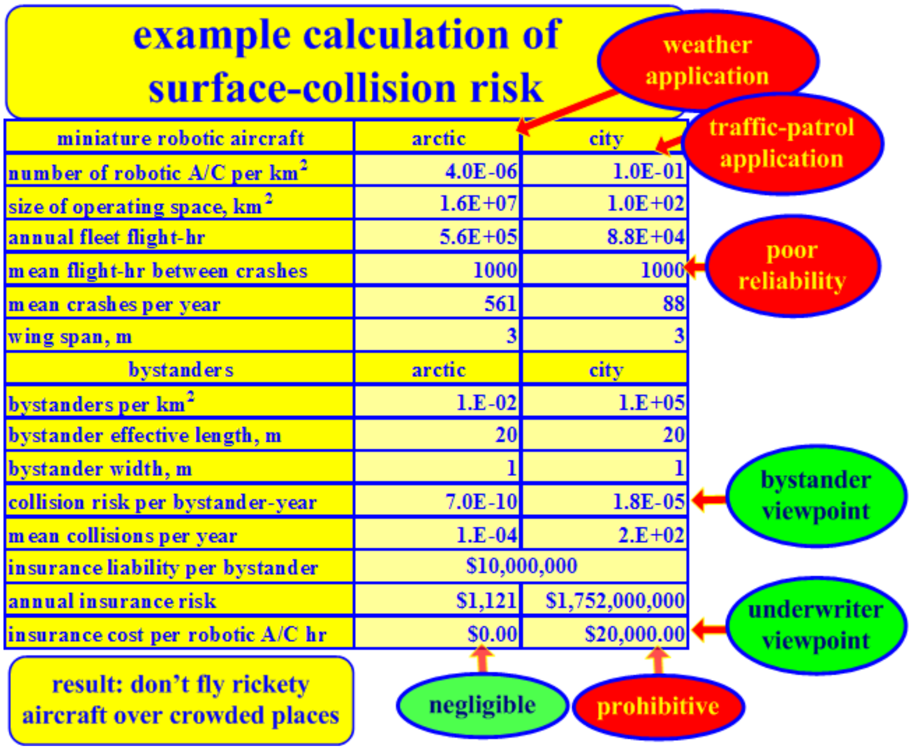


Figure 4. As a complement to the midair-collision calculation in Figure 3, this example compares risk of surface damage for unreliable aircraft flying variously over the arctic or a city. The 1000-hour mean-time-between crashes is somewhat better than robotic aircraft have actually demonstrated, and at this level the risks for flight over a city would entail prohibitively high insurance costs. Hence such work would best be left to manned aircraft. For operations over the arctic, however, poor reliability entails no appreciable risk.

- people aboard the "first-party" aircraft;
- people aboard other aircraft; and
- people and their property on the ground.

Regulation concerns itself mainly with the "first-party" people, since taking care of them also addresses most of the risks for everyone else. But for an unmanned aircraft there is no need to worry about people on board, so the safety focus should not be on the aircraft itself but rather on what it might hit. That in turn means that – unlike for manned aircraft – the *reliability* required to achieve *safety* depends on where the aircraft is flown. Much higher reliability is required for flight over a city than over the open sea (Figure 2).

How much reliability can a prospective entrepreneur afford? Perhaps not much. Designing for reliability, or beyond that, *demonstrating* reliability, is an expensive business: hence the tens of millions required for type certification. But lack of money for reliability need not compromise safety, since the intended operating regimes have few people at risk either on the ground or in the sky. (Otherwise the hungry pilots among them would be stealing our lunch!)

Regulation-by-insurance-risk

It is essential that regulations mandate acceptable levels of risk, rather than acceptable levels of reliability. If they were instead to call for unaffordable reliability, then they would simply prevent any development at all. How then might risk be regulated? As a way to think about the problem, suppose that there were only one regulation, namely this: that no person shall operate an unmanned aircraft without third-party liability insurance satisfactory to the government.

This approach would outsource safety assessment to the insurance market. It would do so without increasing costs, since any responsible operator will carry insurance anyway - hence he will have to make his case to prospective underwriters, regardless of the regulations. Nor should it compromise safety, since sharp actuaries take a back seat to nobody in evaluating risk. They would price risky operations out of the market, while allowing safe operations to proceed.

Figure 3 and Figure 4 demonstrate the point with two sets of risk calculations: one for midair collision, and one for surface damage (*cf*. Anno 1982, McGeer 1994, McGeer *et al*. 1999, Weibel & Hansman 2005, Clothier & Walker 2006).[2] The first takes weather reconnaissance as an example. Suppose that miniature aircraft were used to do the same job over the ocean as is done routinely by weather balloons on land – that is, sounding the atmosphere from near the surface to 20,000 ft or so. Then it turns out that even if the same sky were filled with general-aviation aircraft at the same density as over the continent, and even if next-to-nothing were done to effect separation, and even if the third-party liability coverage was $10M per person, the actuarial cost faced by the operator would be only about $1 per flight-hour. Even this inflated premium would be quite affordable.

By the same token, this example illustrates that, for all the discussion about the critical need to develop sense-and-avoid devices for robotic aircraft, the actual risk being addressed is tiny. In other words, from the point of view of somebody aboard a transiting manned aircraft, the risk of collision with an unmanned aircraft (scattered at the densities reasonably in prospect) is negligible compared with the risks of birdstrike and collision with manned aircraft, not to mention the sundry other hazards that we continually face down as pilots and passengers. It also means that any separation system, whether by air-traffic procedures or some device on the aircraft, need not be highly reliable in itself. Even if it worked in only 9 encounters out of 10, it would still reduce an already tiny risk by another order of magnitude.

Now consider Figure 4, which lists a calculation of surface-collision risk. Here we imagine miniature aircraft raining down from the sky on average once per thousand flight hours – a figure which is barely conceivable by manned-aircraft standards, but for robotic-aircraft would represent a real step forward! It turns out that an aspiring operator trying to compete with a manned traffic helicopter would face an insurance premium in the neighborhood of $20,000 per flight hour. So much for that business plan! But an operator aiming at the arctic would have negligible insurance cost.

This calculation is obviously simplified – for one thing it assumes that damage is limited to the aircraft's cross section, which would not be the case if, for example, it were to start a fire. (I for

[2] The brief note by Anno (1982) is particularly admirable for its simplicity in reviewing midair risk.

one am much more comfortable flying robotic aircraft over the sea than a tinder-dry forest, however sparsely populated.) But it does illustrate that low reliability need not be a safety risk.

Economy and reliability

A further point follows. In aviation circles we often hear furtive talk about cutting corners on safety to save money. Leaving aside the question of whether that might work in one case or another, one should recognise that, in likely robotic-aircraft markets, it is economy rather than safety which sets the higher bar. In the "arctic" example of Figure 4, aircraft could be falling out of the sky on every flight without creating a significant safety hazard, but in most applications such a high attrition rate would not be affordable. On the other hand, a low attrition rate might not be affordable either, and choosing the right level then becomes a design decision.

Again taking weather reconnaissance as an example, our figure of 1000 flight-hours between crashes is a guess at the ultimate attrition rate due to icing (that is, when efforts to avoid losing valuable aircraft to icing are well-balanced against efforts to get valuable data from regions where icing is prevalent). But if weather is going to cause losses at a rate of 10^{-3} per flight hour, it would be wasteful to expend engineering effort or add hardware to make the aircraft's intrinsic reliability much better than 10^{-4} per flight hour, since no significant reduction in attrition would result. Put another way, rather than add redundant systems on the aircraft, it would be more economical, and no less safe, to treat the aircraft themselves as redundant.

This being the case, I am not at all concerned that safety requirements will make robotic aircraft uneconomic. I am, however, very concerned that *regulatory* requirements will make them uneconomic. In practice this is already the situation in the US. The market pull is not so strong that it can overcome even a moderately oversized barrier, so avoiding proscriptive regulation is vital. Of course in some sense perfect safety would be achieved if everybody just stayed on the ground, but that would not be good sense. Robotic aircraft genuinely do promise to provide services of general value, such as better weather forecasts, which are expensive or unaffordable at present. It is an opportunity that we should grasp and not strangle.

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About the author

Tad McGeer's work on robotic aircraft dates from 1990, when he served as Chief Scientist at Aurora Flight Sciences. He headed early design studies on the *Perseus* and *Theseus* unmanned research aircraft, and then proposed the *Aerosonde* miniature aircraft concept for long-range weather reconnaissance. This led to founding of The Insitu Group, beginning in a

Silicon Valley garage in 1992, and moving to the Columbia River Gorge in 1994. Insitu pioneered development of miniature robotic aircraft in worldwide trials through the latter half of the 1990s. In 2000, Dr McGeer led design of *Seascan* for long-endurance imaging reconnaissance. *Seascan* made the longest-ever flight for a ship-based aircraft in 2004, while the *GeoRanger* variant made the first unmanned geomagnetic surveys, and the *Scaneagle* military variant was adopted by the US Marines and Navy. Dr McGeer directed all of Insitu's engineering through 2004, with particular responsibility for conceptual and configuration design, performance, dynamics and control, avionics, algorithms, simulation, and onboard and ground software. In 2006 Dr McGeer founded Aerovel Corporation to concentrate on civil applications of robotic aircraft. He serves as an affiliate faculty member in Aeronautics & Astronautics at the University of Washington. He has been flying for more than 30 years and 2,500 hours, with glider, sea, and instrument ratings.