~~** CONFIDENTIAL **~~

Fly Like a Hummingbird
(without the sting)
or
The Flying Car
or
The Flying Carpet
or
something [concept needs a name]

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1 Caveats

The "vision" described here represents a long-term goal and illustration of the concept; not a short-term intention. The latter section of this document describes some of the issues and technical challenges that will ultimately need to be addressed to achieve the vision.

However, practical, saleable vehicles can be built on the underlying technology short of the "vision". Such early vehicles would be operated by trained pilots and regulated as helicopters in most jurisdictions. Nonetheless, these early vehicles would still have major safety, cost, and simplicity advantages over existing aircraft.

Development and sale of simpler vehicles using key parts of the underlying technologies can be used to fund further development and evolution of the vehicle concepts. Initial markets would be similar to those for existing helicopters and VTOL aircraft: search-and-rescue, passenger and cargo transport, sport, surveillance, etc.

2 The vision

"Liftoff"

You step into your vehicle and settle into your seat as you say "liftoff".

Your voice is recognized as that of an authorized user – the vehicle actually belongs to your wife. There's a quiet click as the charging plug automatically retracts into its compartment, then 100 thrusters - near-silent electric motors, each with a small fixed-pitch propeller – spin up all around the vehicle. Over a few seconds, they gradually take up the weight of the vehicle with you in it.

As they do, the vehicle determines the total takeoff weight by measuring how much power it needs to send to the motors to lift you off the ground. It checks that all the motors are supplying the expected amount of thrust and are running smoothly and in balance.

Oh no - it discovers that 2 of the 100 thrusters are producing less thrust than they should, one is producing no thrust at all, and a fourth is wobbling, probably due to a chipped prop or loose mounting bolts. It shuts down all four, noting the problems with each one in its maintenance log. (You meant to replace a couple of those, but things have been busy.)

96 out of 100 motors in good condition is still within the "green" zone for safe flight[1] and the batteries have enough charge, so the vehicle rises vertically toward it's default hover height, 50 meters above the ground. It automatically maintains its balance, rising level and straight, directing a little extra power to the motors near the 4 failed units.

You stretch out, putting your feet up and opening your magazine. The vehicle senses the beginnings of the tilt as you lean backwards (moving the center of gravity), and shifts some of the thrust that way to compensate.

20 meters up, you rise above the treetops and the gusty wind pushes on the vehicle, but you barely notice because the vehicle's gyro sensors and accelerometers, together with the GPS receiver, sense the movement caused by the wind. Power is shifted to the opposite side as needed to keep you rising straight above your parking spot.

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[1] In the yellow zone, you can continue to your destination, but can't take off again. In the red zone, the vehicle automatically lands at the nearest safe spot – a golf course, park, highway median, rooftop landing zone, etc. It has an on-board database of such spots, updated automatically via a mobile network.

To the garden

You're looking forward to your lunch at the rooftop restaurant (convenient free parking!). Normally, you'd just tell the vehicle "take me to Fred's" and let it do the flying for you[2], but it's a beautiful sunny day and you feel like a quick look at the progress with the cactus-planting at the little garden you designed for the parks department to replace the old freeway interchange, so you lean forward and grab the control knob.

It's a stubby rubber knob an inch high, that hardly moves at all. You give it a gentle twist to the left against its internal spring, and the vehicle yaws the same way, slightly increasing the speed of the clockwise-turning props and decreasing the speed of the counter-clockwise props, to torque the vehicle around. As those ugly apartment buildings across the river come into view, you let go of the knob. It returns to its neutral position and the vehicle stops turning. Then you press the knob forward and the vehicle tilts the same way, shifting a little power to the back and moving forward[3]. The vehicle holds it's altitude and attitude as it moves toward the gap between the buildings.

Your phone rings. You click the "hold" button on the knob and let go of the knob, reaching for the phone in your pocket. The vehicle keeps going exactly on the course and speed you had it.

It's your business partner, who is going to meet you for lunch. She's wrapping up the design for the playground, due to the client this afternoon. Should the water slide empty into the duck pond or the mud bath? The client left it up to you. You find the alternative versions of the plans and stare at each, trying to decide – she can't leave for lunch until this is done.

While your head is buried in the plans, the vehicle has been flying toward the apartment buildings. You didn't really aim it very well – you meant to go through the gap, but it's a small gap and a ways off. On the course you set, the vehicle would collide with the larger building in a few seconds.

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[2] There is an automatic mode where the user chooses only the destination, and a manual mode where the user can fly at will, within limits imposed by safety requirements, ATC rules, airspace restrictions, etc. The user cannot override these limits (except possibly in emergencies).

[3] In manual control mode, the vehicle is entirely fly-by-wire. Instead of directly controlling motor power or control surfaces, the pilot commands a desired attitude, altitude (incl. descent or ascent rate), course, and speed. The vehicle automatically maintains the commanded state until commanded to do otherwise. Automatically enforced rules will limit speed near and distance from obstacles, limit attitude to safe & legal values, etc. These limits might be set differently depending on the qualifications and authorization of the pilot (or lack thereof).

No worry – the vehicle's "4π" radar detects obstacles in all directions[4]. As you get closer to the building, the vehicle gradually slows until it stops, hovering about 30 meters from the building[5]. It emits a soft "beep" to let you know; after all, you were driving it in manual mode and haven't told it where to go next.

You look up from the plans, grab the knob again and this time pull it straight up. The vehicle rises vertically until you can see over the top of the buildings. You let go, looking for the garden as the vehicle stops rising and goes into a hover. You realize you don't remember exactly where the garden is, and your partner is waiting on the phone. So you lean forward and use your finger to drag the map view on the dashboard until it shows the garden, then double-tap on the garden. The vehicle goes into automatic mode, heading for the garden at standard speed and altitude, automatically avoiding other vehicles and going around that big radio tower.

You look back at the plans. Definitely the mud bath. Kids love getting dirty and they can wash off in the hot tub. And who wants to scare the ducks?

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[4] It's called that because there are 4 π steradians in a sphere, but you're not big on geometry. Of course the radar doesn't get confused by pings from other nearby vehicles, because each ping contains a unique source ID and is transmitted on a randomly-chosen frequency. Ping collisions are rare and automatically detected.

Like all systems in the vehicle, the radar is highly redundant and can fly safely with multiple failures. Excessive failures in any system trigger entry into "yellow" or "red" zones.

Redundancy means all components are produced in quantities several times larger than for equivalent non-redundant systems, which makes them cheaper, and also allows each individual unit to have a higher failure rate and shorter lifetime than would be acceptable for non-redundant safety systems (such as are used in conventional aviation); this also reduces their cost.

Some redundancy is mode redundancy instead of physical redundancy. For example, there is only one control knob, but if that fails landing can still be made in automatic mode (and vice-versa).

[5] If you'd continued to hold the knob forward, the vehicle would have approached the building at a continually descending speed until it came to a full stop right next to the building.

There is a time-to-impact calculation running at all times based on the velocity vector and radar-determined distance to the nearest object. The navigation algorithm is aware of the vehicle's maneuvering limits and acts to maintain a constant time-to-impact of a few seconds before objects get close enough that available maneuvering forces are insufficient to prevent collision. (In non-emergency situations much lower maneuvering force limits, chosen for comfort, will be used instead.)

A similar algorithm is aware of the vehicle's amount of available fuel (or battery charge) and distance from a safe landing location. Since descent requires power (the vehicle cannot glide without power or autorotate), this prevents the vehicle from going beyond an altitude or distance from which a safe landing can be made (with safety margins of course).

An emergency override system (for example a button that must be held down while flying) might be provided in case the automatic emergency landing system tries to do something dangerous (for example, attempting to land in a volcano caldera that has recently become filled with hot lava).

You settle the playground plan and hang up – she'll meet you at the restaurant in 20 minutes. You relax, staring out the window you approach the garden. Sure enough, that idiot contractor has mixed up the pincushions with the prickly pears – again. You tell the vehicle to head for Fred's restaurant, while you bang out an email to the contractor, telling him to hire a proper botanist if he can't tell a pincushion from a prickly pear.

Somewhere around your third paragraph describing the difference between a pincushion cactus and a pinhead contractor, you hear a loud bang and feel a small shudder.

Startled, you look around. There's a yellow light on the dashboard. The vehicle continues smoothly toward the restaurant. You glance at the screen – as you suspected, thruster #37 failed – it was loose this morning, but you figured you'd tighten up the mounting tomorrow. Hmm, it seems #38 and #40 are busted too. Those are all on the right – you look over there and see the motor from thruster #37 swinging by it's power cable. The propeller is completely gone – it looks like it must have come loose in flight and whacked into #38 and then #40. So all three are busted. Your wife Alice isn't going to be happy.

With three more thrusters down, only 93 out of 100 are still working. That puts you in the "yellow" zone; it looks like you'll get to the restaurant, but the vehicle won't take off again until you replace some of the thrusters – probably they'll have some in the garage at the restaurant.

As your vehicle settles on your rooftop parking spot, you hear the "snick" of the restaurant's charging plug automatically attaching to the vehicle. The charging light on the dashboard comes on, and the dashboard screen projects 45 minutes to a full charge. You frown a bit as you see the restaurant only offers the first 20 MJ free – enough for about 15 minutes of flight; after that they charge.

As you get out, you pretend you don't notice another customer's disapproving glance at your ragged vehicle (#37 is still swinging on that cable).

A little repair job

After an excellent lunch and maybe a few too many Whiskey Sours, you come back to the garage ready for a good nap. You climb in and say "take me home, Jimmy!". Nothing happens. You see the yellow light is flashing now. Oh, yeah, 93/100 is in the yellow zone - not enough for a safe takeoff.

You briefly think of holding down the emergency button and taking off anyway, but you're not that drunk[6]. Besides, it would be uncomfortable to hold the emergency

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[6] The emergency button allows takeoff while in the yellow zone (while there is still significant redundancy left), but not in the red zone (when the remaining redundancy is too little to allow continued safe flight). In the red zone, the emergency button does allow brief postponement of automatic landing, but only enough to avoid unsafe landing zones.

button for the whole ride home. Why do they put it in such an awkward position, anyway?

You get out and find Fred. He doesn't have any spare thrusters, but says there's a mini-mart half a block north on the surface street. You hop in the elevator and go down. The mini-mart has 4 thrusters on the shelf. And the price is almost double what you pay at the discount store. And two will get you into the green zone; but just barely. But, you think – safety first! Sure, you could get home with just 2 more – 95/100 is enough to get you in the green zone. But you remember the prop on #89 was looking a little cracked the other day; it could fly apart anytime. And at this point you're feeling like you really need that nap – and a couple of aspirin. Plus Alice got really upset that time you had a red zone auto-landing on that median strip. It wasn't your fault that 7 thrusters failed at once – when you took off you had 96 good thrusters - well in the green zone – (ok, *in* the green zone, anyway), then those damn kids with the kite on kevlar line – who flies a kite with kevlar line? And the hailstones! Who could expect that? It wasn't your fault - you were just unlucky, like that other time. Anyway, Alice wasn't happy when she had to come pick you up. So you grab three thrusters (96/100 is pretty good, right?) and check out.

Back up to the garage, you can't get #37 out – it's stuck somehow; probably got whacked good by #40. So you cut off the cable with your nail clippers, and replace #38, #40 and the one with the chipped prop. Each one comes off by pressing the release tab and pulling up – the new ones snap in the same way. The old thrusters go in the garbage can. You'll replace the others next week after you go shopping.

Finally, you get in and hit the 'take me home' button.

What a day!

Why?

Because we want to get out of traffic. Because we wait to avoid dangerous accidents. Because roads and railways are expensive and take up valuable real estate. Because point-to-point travel is faster. Because we want to go places where there are no roads.

3 More caveats

My goal in this document is to describe the core concepts and show that they are workable and practical with present technology. By that, I mean that only engineering work is needed to realize them, not new technical breakthroughs.

In the following sections many assumptions about details are made for simplicity.

For example, the “thruster” is described as using fixed-pitch propellers. It may be that ducted fans actually offer a better tradeoff of power, weight, noise, etc. Which choice is better will eventually be the subject of engineering work during the development process.

The latter parts of this document discuss many of these details and the possible choices to be made.

In the sections that follow, keep in mind that the vehicle and system concept are still high-level and details may change.

4 Technical concepts

4.1 Overview

The core technical concepts:

- Safety through redundancy

Unlike conventional aviation powerplants (piston and turbine engines), electric thrusters are mechanically simple and reasonably efficient at small scale. This makes practical the use of many small thrusters instead of one or a few large powerplants, permitting redundancy.

Machine-enforced redundancy[7] avoids accidents due to failure of critical components or poor maintenance.

- Safety through machine-mediated control

Accidents happen when pilots make errors. Vehicles that can be operated only within a safe envelope cannot suffer accidents due to pilot error.

- Low cost through simplicity and economies of scale[8]

Electric thrusters are mechanically simple compared to piston or turbine powerplants and conventional control systems (esp. those of helicopters). All control is effected by differential power applied to the thrusters, creating a control system that is both simple and redundant.

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[7] Meaning that the vehicle will refuse to fly without a minimum level of redundancy.

[8] As will be discussed below, the limitations of current batteries may require some non-redundant components in near-term vehicles, until batteries improve. This may remove some of the vehicle’s cost advantages compared to conventional aircraft, but only in the near term.

Redundant components can fail without safety implications, so can be manufactured without the high reliability required of conventional aviation components.

Redundant components will require periodic or routine replacement, but will be produced in proportionately larger numbers than conventional non-redundant components, resulting in economies of scale. Because thrusters (the main wear component) are physically small and simple, they can be replaced by untrained users (like changing an ink cartridge).

4.2 Differences from conventional aircraft

4.2.1 Not a fixed-wing airplane

Unlike conventional fixed-wing aircraft, the vehicle:

- Can take off vertically and hover (VTOL)
- Can not stall or spin
- Can not hit terrain or stationary objects (radar, mediated control, automatic navigation)
- Can not hit other aircraft[9]
- Is compact (no wings)
- Is a low-speed, short-range vehicle
    - Yet still far faster than automobiles (no traffic, direct routing)
- Will operate at low altitudes in close proximity to people & structures

4.2.2 Not a helicopter[10]

- No collective or cyclic control system
    - Avoid complexity, cost, and single point-of-failure
- No tail rotor
    - Weight savings, avoid single point-of-failure
- No main rotors
    - No single point of failure, smaller

4.2.3 Safe

- No (or minimal) single point of failure
- Can fly safely with multiple failed engines, props
- Auto-landing
- Automatic anti-collision

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[9] Eventually; depends on implementation of airspace/ATC rules and instrumentation in other aircraft types.

[10] Near-term vehicles will be considered helicopters for regulatory purposes, and will require a helicopter-rated pilot. Eventually a new regulatory category will be needed for vehicles operated by non-pilots.

4.2.4 Low-maintenance

- No complex piston or turbine engines
- No complex control systems
- Nothing to lubricate or maintain
- Easy modular replacement of parts (done by end user)
- Self-monitoring; tells you what it needs and when
    - Knows how much risk is "too much"; won't let you exceed that

4.2.5 Low operating cost

- No fuel (electrically powered & recharged)[11]
- Skilled pilots not required
- Maintenance burden no higher than for automobiles (safety implications zero)
- Cheap, simple, disposable parts are produced in large volumes
    - 10s to 100s per machine (plus replacements)
    - High-reliability parts not required

4.2.6 Low acquisition cost

- Powerplants produced in large volumes – economy of scale
- Automotive (not aviation) quality sufficient due to redundancy
- No complex and expensive piston or turbine engines

4.3 Safety

Many different kinds of safety concerns are among the reasons why personal aircraft have not yet become ubiquitous.

A mature vehicle of the type described can not only be far safer than existing general aviation, but safer than today's automobiles.

4.3.1 Safety through redundancy

Today's automobiles, quite safe by any reasonable standard, do have single points of failure. A front tire blowout at high speed or steering linkage failure can lead to rapid loss of control and a fatal accident.

- Key to safety is redundancy and lots of it
    - No single point of failure
    - Vehicle is safe even with multiple independent failures
    - Automatic landing if redundancy level becomes too low
    - Poor maintenance cannot lead to safety problems
        - Instead, vehicle lands or refuses to fly

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[11] Once batteries advance to allow all-battery operation.

4.3.2 Safety through machine mediation

Manually-driven vehicles without any layer of protection against incompetent (or even malicious) drivers have a certain inherent risk. Fully automatic navigation is much easier to implement in the air than on obstacle and traffic-filled highways.

4.3.2.1 Automatic pilotless flight

Fully automatic flight – where the passenger simply inputs his destination – is possible with today's technology, but not with today's airspace rules, air traffic control (ATC) system, and related aviation regulatory structure. These will require major revision to permit automated passenger vehicles.

The problem of pilot-less aircraft is inherently much easier than that of driverless cars, yet these already seem to be on the horizon[12]. Unlike a car, a pilotless aircraft does not need to deal with pedestrians, roads (and road rules), road obstructions, and nearby traffic. The requirements for pilotless aircraft operating at low altitudes (0 to 1000 feet AGL) include:

- Reasonably accurate 3D terrain maps
    - For navigational planning to avoid terrain
    - On-board, perhaps updated/augmented by online updates
    - Google Earth already offers a sufficiently good map (probably)
    - Ideally, this would include low-level obstructions such as towers, power lines, etc.

- Radar (or other sensor) system able to detect nearby obstructions
    - At least in the direction of travel; ideally in all directions
    - Sonar, LIDAR systems might work too (even cameras w/suitable image processing)

- A means of detecting the presence of other nearby flying vehicles
    - And their short-term flight paths (to plan non-colliding routes)
    - Method must be local and decentralized to be robust against infrastructure failures (avoid centralized databases, non-local communication requirements)
    - One method would be mandatory short-range (< 1000 meters) broadcast of GPS coordinates and velocity vector of all vehicles. Other nearby vehicles would receive these transmissions.

- Standardized "rules of the road" to determine right-of-way and collision-avoidance algorithms to be followed by all vehicles
    - Existing rules mostly provide for this, but they would have to be codified in unambiguous algorithmic form, and thoroughly tested (in simulation) for correctness and efficiency.

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[12] http://en.wikipedia.org/wiki/Autonomous_car, 2012-03-15

    - For high-traffic situations, “flocking algorithms” would be needed to allow vehicles to cooperate to dynamically establish flight corridors, establish traffic separation, and avoid route conflict[13]

- Database of safe landing zones[14]
    - On-board, probably updated/augmented by online updates
    - Database must be “dense” enough to provide multiple nearby safe landing zones (at least emergency landing zones) for all travel routes.
    - Emergency landing zones could make use of existing reserved spaces such as highway median strips, rooftops, etc.

- A regulatory environment that permits pilotless aircraft to operate in the immediate vicinity of populated structures
    - Exemption from ATC oversight (at low altitudes) or automated interactions with ATC

4.3.2.2 Computer-mediated piloted flight

Before fully autonomous vehicles are permitted, and even afterward when passengers so desire, an untrained person can safely guide the vehicle via computer-mediated flight.

Assuming the same requirements as for fully automated flight (above), an automated system can mediate between human control inputs and vehicle response to make unsafe flight commands impossible.

Pilot input would be fly-by-wire, via a “3D mouse”, something like a SpaceNavigator[15]. This receives commands in 6 degrees of freedom – pitch, roll, yaw, X, Y, and Z.

Pitch, roll, and yaw inputs would command a corresponding change in vehicle attitude, X, Y, and Z inputs would command the vehicle to translate along these axes[16].

The control input commands changes in attitude or velocity; if the control is released the vehicle will maintain the commanded attitude or velocity vector.

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[13] There is a fair-sized body of existing research on this. And of course birds do it already.

[14] This assumes a fairly “dumb” autopilot that isn’t capable of looking and finding safe landing areas by itself. If machine intelligence and image processing is advanced enough to make reliable autonomous cars, it probably can also do this by itself. As of 2012, this is not yet off-the-shelf technology, so it is not assumed.

[15] http://www.3dconnexion.com/products/spacenavigator.html, 2012-03-15

[16] In practice, vehicle attitude and translation are coupled such that one usually implies the other, but I’m not going to go into that here.

Controls (probably just buttons) would be provided to command the vehicle to hold altitude, enter a hover (stop all translations), etc.[17]

However, the range of vehicle attitudes would be limited by the automatic system to stay within safe limits – no matter how long the user holds the "roll left" command, the vehicle will not flip upside-down, but will roll only to the safe limit.

Similarly, the translation commands would be vetted by the automatic system for safety and to avoid collisions – if the user commands the vehicle to fly forward into a building, the sensor system will detect the building and reduce speed (while still moving in the commanded direction) to avoid collision, ultimately coming to a full stop next to the building.

These translation checks would include conformance with airspace and ATC rules, right-of-way rules, flocking rules, etc. – if the vehicle approaches prohibited airspace, the vehicle would treat the boundary of the prohibited airspace in the same way as the wall of a building – by slowing to avoid entry into the prohibited space. Rules such as speed and altitude limits, noise abatement procedures, etc. would be similarly enforced with "invisible" walls and limits[18].

The computer mediated piloting system would also check if the pilot attempts to stray too far from a safe landing zone, becomes low on battery power or fuel, or encounters another unsafe condition. If this occurs, the system would prompt the pilot to take corrective action, and would intervene if necessary to force a return to a safe flight path, or a landing.

Mediated manual navigation (with built-in anti-collision algorithms) will be vastly safer than today's piloted control. In a properly implemented system, even *intentional* collisions and airspace violations should be impossible.

4.4 Thrusters

A core technology for this vehicle concept is the modular "thruster" unit.

The thruster consists of:

- DC brushless motor (probably "outrunner" type)
- Fixed-pitch prop
- Simple motor control electronics
- Ideally, batteries to power the thruster for a normal flight duration

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[17] See Apollo LM control modes as described in *Digital Apollo*, http://mitpress.mit.edu/catalog/item/default.asp?ttype=2&tid=11416

[18] Per the discussion elsewhere in this document, these might in some circumstances be overridable by the pilot in an emergency situation.

4.4.1 Brushless DC Motors

The brushless DC motor (BDM) is a relatively new technology. These motors offer high power-to-weight ratios, zero maintenance, and low cost, together with reasonably long life (at least in versions designed for that purpose).

They are already (2012) manufactured in large volumes, at low prices, and in sizes appropriate for the described vehicle thrusters, for the hobby R/C airplane market.

A critical difference from conventional aviation powerplants (piston or turbine) is that BDMs are electromagnetic devices and *not heat engines*. Unlike a heat engine, there is no thermodynamic advantage to large size. Heat engines leak heat – therefore efficiency requires they either be large (to reduce the rate of heat loss) or run fast (before heat escapes). Fast-running motors wear out quickly, and large motors cannot be used in large numbers for redundancy and economy of scale. BDMs make high levels of motor redundancy practical.

4.4.2 Thruster characteristics

Thrusters are:

- Modular and self-contained
- Easily replaced (as an entire unit) by untrained people (think changing an ink cartridge)
- Inexpensive and disposable
- Used in large, highly redundant arrays

A single thruster might consist of a single motor/prop assembly, or (perhaps more likely) of a pair of counter-rotating motor/props, able to cancel each other's torque. A counter-rotating pair could be mounted either co-axially (may be efficiency advantages), in parallel (simpler), or overlapping by up to one prop radius (a compromise).

Electric thrusters can be cheap compared to conventional aviation powerplants because they are:

- Vastly simpler than a reciprocating or turbine engine
    - No combustion, limited temperatures
    - No corrosive or unstable chemicals (gasoline, oil, etc.)
    - No throttles, valves, carburetors, mufflers, fuel pumps, etc.
    - No routine maintenance items (filters, oil, spark plugs, etc.)
    - Only one moving part (the rotor)

- Used in highly redundant arrays
    - Redundancy removes need for high quality and reliability in individual components (automotive-grade quality sufficient); do not have to meet conventional aviation reliability standards

    - Large thruster arrays imply very large quantity manufacture of thrusters (compared to conventional powerplants); economies of scale apply

- Propellers are simple single-piece parts
    - No variable-pitch or reverse-pitch mechanisms
    - No moving parts
    - No control surfaces
    - No linkages
    - No exotic materials required

As a result, thrusters can be disposable, consumer-replaceable units. They will not require the expertise or equipment of a qualified A&P to maintain or replace.

Being electric, thrusters are inherently quieter than reciprocating engines (although prop noise is a separate issue).

Existing technology (2012) allows for motor/prop combinations that can lift more than 10 times their own weight[19]. Today's lithium-ion (Li+) batteries are good enough to allow a flight time of 20 to 40 minutes[20] while lifting a payload 2 or more times the weight of the prop/motor/battery thruster.

Clearly, a major challenge is energy density (joules/kg) and cost of batteries. Happily, large R&D efforts are already in place here, driven by applications as diverse as wind and solar power systems, laptop computers and electric cars. We can anticipate progress, and in the meantime, there appear to be interim workarounds.

4.5 RAIT

Another core concept is redundant arrays of inexpensive thrusters (RAIT)[21].

Very large numbers of small thrusters (many dozens to hundreds per vehicle) allows lots of redundancy, which offers tremendous safety advantages, even compensating for poor consumer-level (automotive-level) maintenance, compared to what is considered normal in aviation.

From an engine-failure viewpoint, a RAIT vehicle with 100+ thrusters (and ample safety margin) can be far more reliable than existing multi-engine aircraft, even with poor maintenance.

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[19] See performance analysis.

[20] See discussion below for ways to lengthen the flight time in the interim before improved batteries are available.

[21] Might "RAIM", for inexpensive Motors, be better? I think not.

4.5.1 Control with RAIT

The RAIT array supplies not only lift, but also all necessary control for the vehicle.

RAIT allows elimination of all conventional control systems - there are no flaps, ailerons, rudders, or elevators, no cyclic, collective, or tail rotors, no pulleys, rods or other control linkages, no hydraulics or servos, and none of the single points of failure these imply.

Instead, the RAIT control system is simple, redundant and cheap.

All control is by means of modulated power (differential RPM) to the thrusters. The only moving part in the control system is the rotating propellers also used for lift.

Pitch is controlled by differential thrust to fore and aft thrusters, and roll is controlled by differential thrust to port and starboard thrusters.

Yaw is controlled by reaction from differential acceleration of counter-rotating thrusters; each spinning prop has momentum and acts as a gyroscope. By changing the rotation rate, a yaw can be imparted to the vehicle[22].

As in a helicopter, climbing is achieved by adding vertical thrust, descent by reducing it. Forward motion comes from pitching forward, turns come from roll and yaw.

The control algorithms needed are complex, but are within the existing state-of-the-art. Lift margin will be reserved for continued control in the event of failed thrusters – thrusters will operate at less than maximum capacity in normal operation. The control algorithms will automatically compensate for changes in the vehicle's center of gravity (as passengers move around), wind deflection, etc.

The RAIT control system will also sense the total payload weight, as a proportion of the maximum safe flight weight (after allowing for necessary redundancy), and will not allow flight in overloaded conditions.

Modern MEMS-based solid-state gyro sensors and accelerometers are tiny, inexpensive, and draw low power compared to sensors used in conventional aviation systems. These are already widely used in UAVs and hobby aircraft.

4.5.2 Redundancy levels (green, yellow, red)

Conventional multi-engine aircraft are designed to continue flight with an engine failure – at least long enough to make a safe landing. But operation with a failed engine is not considered normal or safe – it is an emergency operation mode. Because there are only a few engines, each engine contributes a very large fraction of the power needed for flight.

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[22] This is an oversimplification, but it should work. See http://en.wikipedia.org/wiki/Control_moment_gyroscope .

Once a single engine has failed, the risk of losing another engine, and a likely forced landing or crash, is unacceptably high.

With a very large number of thrusters providing a large amount of redundancy, multiple thrusters can fail and still leave adequate redundancy for continued safe flight. If there are 100 independent thrusters, and only 70 are needed for flight, and each thruster has an independent probability of failure, the threshold where the safe flight regime ends and the emergency regime begins does not need to be at 99 working thrusters.

This means that, up to a certain point, we can *let thrusters fail* without considering the situation to be unsafe or require immediate landing. We can even safely begin a flight with less than 100% of thrusters operable, if the number of good thrusters is above the safe threshold.

I've called this situation the "green zone". Here, flight is considered safe.

Some number of failed thrusters will be considered too many for normal, safe operation, but still sufficient for temporarily operation. I've called this the "yellow zone". Here, a flight already in progress may be completed (at least for some period), but further takeoffs are not permitted. This is analogous to a conventional multi-engine aircraft with a single engine out.

Finally, in the "red zone", so many thrusters have failed that immediate landing is required. In order to avoid accidents, the "red zone" threshold must be set well above the point where the vehicle can no longer fly. As soon as the "red zone" threshold is passed, the vehicle would immediately land at the nearest safe location[23].

For example, if in a vehicle with 100 thrusters holding altitude is impossible with less than 70 operable thrusters, the "red zone" might be set at 80 thrusters, and the "yellow zone" at 90 thrusters. More than that would be the "green zone".

In practice, the thresholds for the different zones would be set not simply on an absolute number of thrusters, but also as a function of loading (less working thrusters are needed for safe flight at lower weights) and perhaps also the distance to the nearest safe landing spot, prevailing winds with relation to that landing spot, etc.

4.5.2.1 Emergency overrides

In aviation it is conventional for automatic systems (and even regulatory rules) to yield to the pilot's determination of necessity in emergency situations.

In this spirit, the automatic landing system and many (or all) automatic safety systems might be overridden by the pilot in an emergency. The degree to which this is permitted

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[23] The vehicle has an on-board database of safe landing locations.

might depend on the training and qualifications of the pilot (untrained pilots might be better off without this ability).

If such an override system is provided, probably the vehicle should record the circumstances under which it is activated, so that after-the-fact determinations can be made whether the deviation was justified or endangered others. The risk of penalties for unjustified use of override ability might be enough to prevent irresponsible use of the override mode (esp. by untrained pilots) in a way that endangers people on the ground or other aircraft.

4.6 Performance

- Range – short compared to airplanes (similar to helicopters; less at first)
    - Not a replacement for conventional aviation
    - Limited by battery capacity & mass
    - Exception: Winged model. Clip-on wings? Different models? Wings are much more efficient at producing lift >> speed & range

- Speed – slow compared to airplanes (similar to helicopters)
    - Maybe similar to automobiles, but can fly direct, no traffic delays; full speed for most of trip; net is much faster than automobiles. No need for infrastructure such as roads, bridges.
    - Exception: Winged configuration (maybe modular) can be as fast as piston airplane; tradeoffs

- Ceiling – Limited by battery life & atmospheric density
    - Cabin not pressurized – avoid high altitudes/high climb/descent rates (comfort). Vehicle normally operates below conventional air traffic (very low altitudes)

4.7 Navigation and airspace utilization

The very first versions of the vehicle, without automated navigation or fully computer-mediated piloting, will require trained pilots and be classified as helicopters for regulatory, licensing, and airspace purposes.

As increasing degrees of automation and computer-mediation become available, the piloting skill required will decrease (eventually to zero) and new rules will be appropriate. This will be increasingly important once the number of vehicles in operation becomes large – a very few (similar to the numbers of helicopters currently in use) can be handled by the existing ATC regime, but the current system is not capable of handling very large numbers of flying vehicles.

In the longer run, automated and fully computer-mediated vehicles (which can be considered the same way) will co-exist with conventional aviation – fixed wing GA aircraft, helicopters, commercial airliners, military traffic, etc.

The vehicles described inherently fly low and slow. To be useful, they will not be based at airports, but will operate in the immediate vicinity of building and people. They will not be pressurized or have oxygen systems, so cannot operate at very high altitudes. Without wings, most power will be devoted to lift (instead of forward propulsion), limiting forward speed to less than 120 miles/hour [probably; possibly less; TBD].

The best way to cope is to divide this type of vehicle traffic from conventional aviation by altitude – given the short distances and low speeds these vehicles will be traveling, there is very little reason for them to operate at high, or even medium altitudes. They should primarily operate within 750 feet of the ground.

Airspace at such low altitudes can be treated separately from higher altitude airspace, which could continue to be operated as it is today. Except for small takeoff and landing corridors around airports, conventional aircraft (helicopters excepted)do not operate at these low altitudes in populated areas (indeed, this is generally prohibited by existing regulation).

Any new rules and regulations introduced for such vehicles (right-of-way, anti-collision sensor requirements and rules, operation near populated structures, noise abatement, flocking rules, etc.) could apply only below a low altitude threshold. Of course these rules will require considerable study and extensive testing, including simulation, before implementation.

5 But will it fly? Some crude numbers.

"With enough power, *anything* will fly."
-- unknown (sometimes attributed to Howard Hughes)

This section provides some numbers for performance and cost of components given existing technology.

As a confirmation, note that electric-powered military VTOL UAVs are both practical and widely-deployed (already), and that hobby-type electric VTOL flying vehicles (quadcopters, open-source "Mikrokopter" etc.) are widely available at a variety of rapidly declining price points today. Consider these as existence proofs.

So let's look at some numbers. Will it fly?

U:\Users\dave\data\
Projects\Flying carpe

The crude spreadsheet above collects some data and simple calculations that will give a back-of-the-envelope sense of the practicality of such a vehicle.

The analysis starts with the characteristics of "thrusters". Data for 10 combinations of brushless DC motors and propellers have been collected from various Internet sites; these are all intended for use in electric-powered radio-controlled (RC) hobby aircraft. The motors range from 52 grams/80 watts to 1.5 kg/6000 watts, and the propellers from 8 to 27 inches in diameter. Retail pricing ranged from $20 to $350 each for the motor/prop combinations.

All the propeller/motor combinations are taken from those suggested by vendors for use in RC aircraft, but motors vary in speed and torque, and propellers vary not only in diameter, but also in pitch, airfoil, and number of blades[24]. The particular combinations chosen are certainly not optimal for this application, but will illustrate what is possible with today's off-the-shelf technology.

While it's true that equipment for RC modeling is likely designed for a short lifetime (MTBF, etc.) compared to conventional aviation standards (typically 100 hour inspections and 2000+ hour TBO), keep in mind that the brushless DC motor/prop combination is mechanically extremely simple – there is only a single moving part (the rotor/prop). The only wear item is the bearing. Production of reliable thrusters should be trivial compared to what is required for a reliable piston or turbine engine.

For simplicity, all the analysis here accounts only for the weight and cost of the motor, propeller, and batteries. The necessary motor control electronics and wiring will represent only a small fraction of these weights, so are ignored for now. The weight of the rest of the vehicle (airframe, avionics, cabin, etc.) is included in the "payload" weights.

5.1 Thruster analysis – no batteries

Start with the top part of the spreadsheet (above the yellow line). This looks at motor/prop combinations without considering battery weight. Input values are unshaded, computed values are in tan.

From left to right, briefly, we have:

> Propeller diameter (inches), pitch (inches/revolution), number of blades, and mass (g).
>
> Motor type, Kv (RPM/volt), maximum current (amps), number of Li+ cells needed in that configuration (3.7 volts each, nominal).
>
> We then calculate the maximum power used by each thruster (watts).

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[24] And, as mentioned elsewhere, simple independent props may not be the optimal thruster. Equally simple arrangements include ducted fans and overlapping counter-rotating props of various configurations. These may end up performing better than the single prop model analyzed here.

Then we have the mass of the motor (grams), maximum thrust produced (ounces and grams), and "net lift" (thrust less weight of motor and prop, grams).

From these we calculate some key values:

Thrust : weight ratio – ranges from **9 to 13** (weight of motor and prop only).
Thrust efficiency – ranges from **3 to 7 kg thrust/kW.**

Given that the motor/prop combination data are from an almost random selection of online offerings, and not at all optimized for this application, I think taking the highest (of 10) values for thrust : weight and thrust efficiency is conservative. A fully optimized design will surely do better[25].

From the "Li+ specific energy" worksheet, we obtain:

Li+ specific energy – 360 to 900 kJ/kg; **I'll use 750**.

This is the amount of energy[26] storable in a kilogram of lithium-ion battery; as will be seen, it's another key number. 750 kJ/kg is close to the highest value I found specified for off-the-shelf 18650 cells (March 2012). This is perhaps less than maximally conservative, but it is well below the maximum value of 900 given by Wikipedia (2012-03-12), and the capacity of commercial Li+ cells has been slowly but steadily increasing, so it seems likely that this will be an achievable number in the very near future, if not already.

5.2 Vehicle analysis – no batteries

Also in the top spreadsheet section, two vehicle models are considered, a "4 person vehicle" (1000 kg "payload") and a "1 person vehicle" (200 kg "payload"; this would be an early prototype vehicle).

As mentioned above, these "payload" weights[27] include the entire weight of the vehicle and payload other than thrusters and batteries.

For comparison, a Cessna 172 (common 4-place light airplane) weighs 767 kg empty (including engine), and has a max gross weight of 1111 kg. A Robinson R22 (common 2-place helicopter) is 389 kg empty (with engine) and has a 635 kg max takeoff weight[28].

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[25] Although I've tried to use values I think are conservative, be aware that the numbers and calculations are crude; reality could easily be different by 20 or 30%. This doesn't change the conclusions significantly.

[26] A kiloJoule (kJ, 1000 Joules) is the amount of energy in 1 kilowatt (1000 watts) of power for 1 second.

[27] SI weights are properly measured in Newtons, not grams, but for familiarity all weights are given in kg-force units.

[28] Weights per Wikipedia, 2012-03-13

For each of the 10 motor/prop combinations, we calculate:

- Number of thrusters needed to lift the fully-loaded vehicle (no allowance is made for failed thrusters; probably about 30% should be added for that).
- Power (kW) consumed by vehicle at max power
- Cost of thrusters (parts only)
- Weight of all thrusters ("Empty kg")
- Energy cost at $0.10/kwh (assumes 100% conversion efficiency to the battery)

Again taking the best of the 10 un-optimized values, we get Table 1:

Table 1 – Without batteries

	4-place vehicle	**1-place vehicle**
Power (electric)	162 kW	32 kW
Cost (thruster parts only)	$ 12,477	$ 2495
Thruster weight	87 kg	17 kg
Max takeoff weight	1087 kg	217 kg
Energy cost	$ 16/hour	$ 3/hour

Without allowance for the battery, the numbers look very favorable.

5.3 Thruster analysis – Li+ batteries

In the spreadsheet section below the yellow line, the same analysis is performed, except this time allowing for enough Li+ batteries for a 25-minute flight time[29]. A 25 minute flight time is not enough for most practical vehicles, but it is enough for a prototype test vehicle.

Including the weight of the battery gives these much-reduced metrics:

Thrust : weight ratio – 1 to 2.5 (weight of motor, prop, and batteries)

And after subtracting battery weight from the thrust:

Thrust efficiency – 0.3 to 4.9 kg thrust/kW

5.4 Vehicle analysis – Li+ batteries

Using the same performance values as above, and 750 kJ/kW for the Li+ specific energy, but taking into account the weight and cost of 25 minutes worth of Li+ batteries are considered, we get Table 2:

---

[29] The per-thruster battery mass was simply adjusted to produce a flight time of 25 minutes (1500 seconds).

Table 2 – With 25 minutes of Li+ batteries

	4-place vehicle	1-place vehicle
Power (electric)	240 kW	48 kW
Cost (thruster & battery only)	$ 106,511	$ 21,302
Thruster & battery weight	662 kg	132 kg
Max takeoff weight	1662 kg	332 kg
Energy cost	$ 24/hour	$ 5/hour

The cost of the 25 minutes of Li+ battery is about 7.5 times the cost of the motor + prop; this is very different from conventional aviation, where engines are expensive and fuel tanks are cheap.

Something similar has happened with the weights – the battery weighs almost 7 times as much as the motor + prop combination.

Adding more battery greatly reduces the net lift (after battery weight) available from each thruster, and so increases the number of thrusters needed. Flight times beyond about 30 minutes generally require impractical numbers of thrusters, and flight times beyond about 45 minutes are impossible (a thruster cannot lift that much Li+ battery at all).

These values are consistent with typical endurance for current (2012) Li+ powered military UAVs and RC hobby VTOL aircraft, which confirms the validity of the model.

5.5 What does this mean?

These numbers show that with 2012 Li+ battery technology (~ 750 kJ/kg), a working VTOL electric vehicle can be built, but it will have very limited endurance, in the range of 20 to 30 minutes flying time. Beyond that, battery weight rapidly becomes most of the weight of the vehicle.

Further, Li+ batteries are very expensive. Our 4-place vehicle requires only $12,477 in engine and prop parts cost, but over $90,000 in batteries for the 25 minute endurance.

Flight endurance is directly proportional to specific energy of the battery – if the battery can store twice as much energy, the endurance time doubles.

These results show that *prototyping* and *test flying* of full-sized vehicles can begin today, but practical battery powered vehicles will have to await significant battery improvements – by at least a factor of 3.

5.6 An interim plan

Improved batteries would be an extremely important development in many fields – renewable energy, automobiles, portable electronics, etc. For this reason large sums are already being invested in battery R&D. These are producing slow but steady results; today's batteries are at least 50% better than those of a few years ago[30].

Eventually, a real breakthrough will appear – for example lithium-air batteries offer about 9000 kJ/kW[31], and there are many other promising approaches. But breakthroughs are unpredictable.

Conventional fuels offer much higher specific energy:

Table 3 – Specific energy[32]

Media	**kJ/kg**
Hydrogen	123,000
Gasoline (petrol)	47,200
Diesel	45,400
Propane (LPG)	46,400
Jet fuel (kerosene)	43,000
Alcohol (ethanol)	26,800
Coal	24,000
Wood	16,200
Lithium air battery	9000
Li+ battery	750

So let's consider an interim alternative, until better batteries are available, based on conventional fuels. The obvious candidates are:

- Fuel cells
- Small turbine engine + generator
- Piston engine + generator
- Rotary (Wankel) internal combustion engine + generator

Each can generate a large amount of power in a small space and limited weight.

Fuel cells produce electric power directly. The heat engines all require a generator and will incur efficiency losses, but these should be less than 50%, and the high specific energy of conventional fuels should make this acceptable.

The vehicle is safe partly because of the high level of redundancy made possible by electric thrusters. But scaling issues with heat engines (and possibly fuel cells) imply a

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[30] I can't find good references for this right now, but that's my observation of battery specifications over the last 5 to 10 years.

[31] http://en.wikipedia.org/wiki/Lithium_air_battery, 2012-03-14

[32] Data from http://en.wikipedia.org/wiki/Energy_density, and http://hypertextbook.com/facts/2003/RoxanneGarcia.shtml, both 2012-03-14

single, non-redundant, power plant (or at best a few for limited redundancy). How can we retain the advantages of a highly redundant system with a single power plant?

Consider the last section of the spreadsheet (below the purple line). This is the same analysis performed above, except with enough Li+ batteries for an endurance of just 5 minutes – an emergency power reserve for use when the main power plant fails. Table 4 gives the results:

Table 2 – With 5 minutes of Li+ batteries

	4-place vehicle	**1-place vehicle**
Power (electric)	173 kW	35 kW
Cost (thruster & battery only)	$ 26,042	$ 5208
Thruster & battery weight	178 kg	36 kg
Max takeoff weight	1178 kg	236 kg
Energy cost	$ 17/hour	$ 3/hour

This is a dramatic improvement over the 25-minute Li+ battery model.

Compared to that model, the 5-minute endurance model (enough battery power for a safe emergency landing after failure of the main power plant[33]) saves over $80,000 in battery cost and 484 kg in battery weight for the 4-place vehicle.

Draining the battery in 5 minutes is (by definition) a 60/5 = 12 C discharge rate. This is well within the capacity of off-the-shelf lithium polymer (LiPo) cells, which have very similar characteristics to conventional Li+ cells (at a bit higher cost).

If a single 250 kW (electrical output[34]) power plant with a few hours' liquid fuel supply is achievable for less than $80,000 and 484 kg, then a practical and safe vehicle with all the advantages described can be built with today's technology, at a price similar to that of a conventional helicopter.

[It seems plausible that a conventional powerplants can meet this requirement, but I haven't run the numbers yet. Best bet is probably a small turbine/generator like an aircraft APU[35], a Wankel-type engine with a generator, or a fuel cell.

---

[33] The vehicle is anticipated to operate mainly at low altitudes, from which a safe landing can easily be accomplished within 5 minutes. But in the event of a power plant failure at an unusually high altitude - from which a normal descent might require more than 5 minutes – the vehicle can, in the emergency, descend in a free fall at the drag-limited terminal velocity (probably 50 to 100 meters/second; 10,000 to 20,000 feet/minute), then use the 5 minutes of battery power to decelerate and transit to a safe landing spot. This would be very uncomfortable for passengers, but not life-threatening.

[34] 250 kW is 335 horsepower. An engine larger than 335 hp is needed because conversion to electricity is not 100% efficient.

[35] http://en.wikipedia.org/wiki/Auxiliary_power_unit

- The Mazda 13B-MSP Renesis auto engine (Wankel) produces 250 hp[36] and weighs 122 kg[37]. (Wankels have a lot of power for their weight.) Something like a pair of these would do it. Probably would need a custom-designed generator.
- The next-gen Mazda engine due for release 2013-2014 (the "16X") looks better yet; it will be lighter and more powerful.[38]
- I've found it difficult so far to get weights and specifications for aircraft turbine APUs. I suspect they can meet the requirements, but at high cost.]

5.7 What will it look like?

The figures below show simple top-view diagrams of the 4-place vehicle. [They're horrible; I'm no artist.] The vehicle cabin dimensions are shown, somewhat arbitrarily, as 48 inches wide by 96 inches long (4′ x 8′).

For comparison, the cabin width of a Cessna 172 is 39.5 inches; the outside dimensions of a 2005 Toyota Prius are 68 x 175 inches (includes side-view mirrors, engine and trunk area).

Figure 1 shows the 4-place vehicle using 51 thrusters, each with a 27 inch diameter prop.

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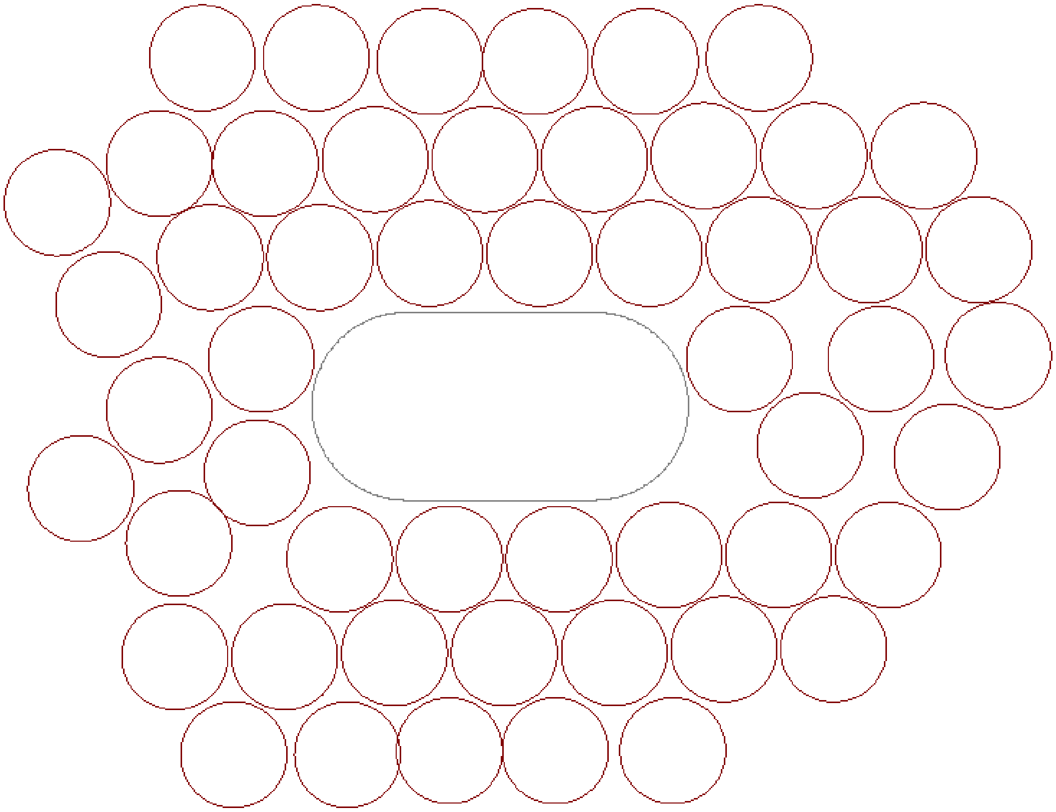
[36] http://jdmspecengines.com/mazda-engines/13b-series/13b-msp-renesis.html

[37] http://en.wikipedia.org/wiki/Mazda_Wankel_engine

[38] http://www.mazda.com/mazdaspirit/rotary/16x/



3/15/2012 6:17:52 PM f=0.96 U:\Users\dave\data\apps\EaglePCB\projects\FlyCar drawings\FluCar1\51x27.brd

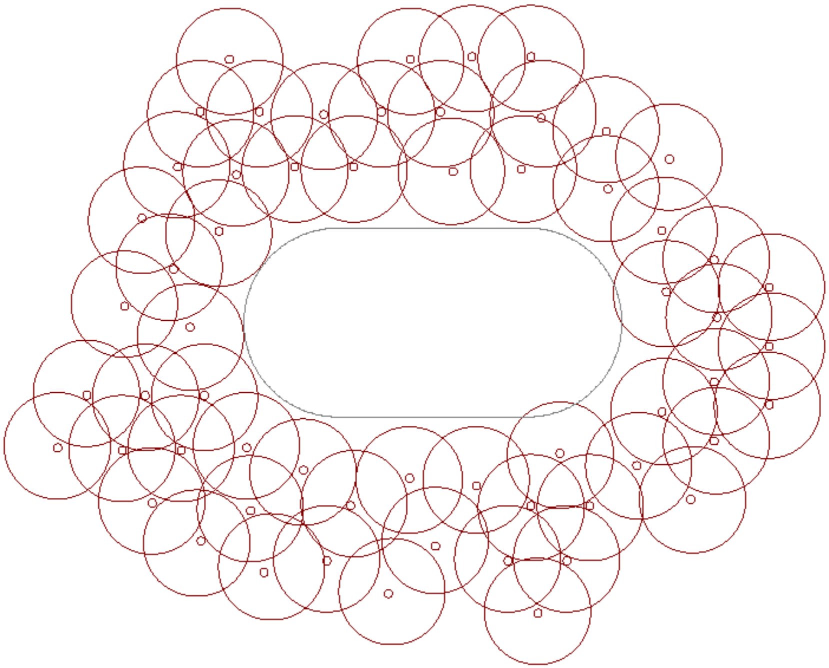
Figure 1 – 4-place vehicle, 51 x 27″ props, no overlap

In this figure the propellers are all in the same plane, without any overlap. The area occupied by the propellers is approximately 280 square feet, compared to the 32 square feet (4′ x 8′) of the cabin.

Unsurprisingly, the resulting vehicle dimensions are on the same order as those of a conventional helicopter of similar weight. It is a large ungainly vehicle.

The total area occupied by propellers would be roughly the same if using a larger numbers of thrusters with smaller propellers. [I haven't the patience to draw in 150 little circles, but the area differs by only about 20% with 151 x 18″ props, and this number is probably more dependent on the match of propeller to motor than on the absolute diameter of the propellers.]

Figure 2 below, at roughly the same scale, shows the same vehicle with the same propellers, but with the propellers offset vertically to allow them to overlap by nearly the radius of each disc. The intention is that each overlapping layer of propeller disc will be rotating in the opposite direction.

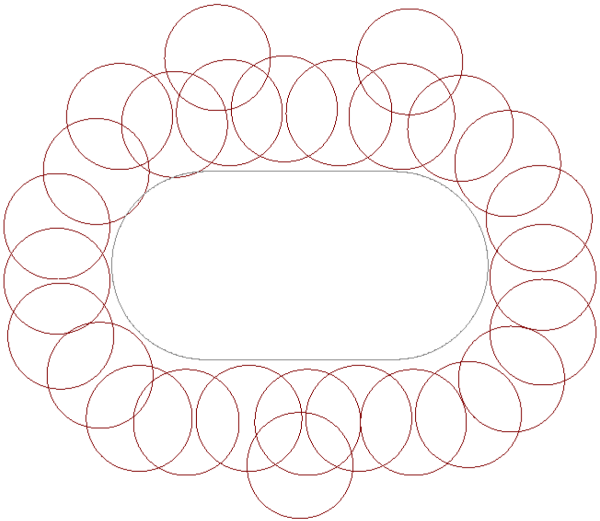


3/15/2012 6:12:11 PM f=1.18 U:\Users\dave\data\apps\EaglePCB\projects\FlyCar drawings\FluCar1\51hx27.brd

Figure 2 – 4-place vehicle, 51 x 27″ props, 50% overlap

This results in a more compact vehicle. The efficiency consequences of the overlap are unclear at this time [to me].

Finally, Figure 3 below shows the same vehicle but with each pair of counter-rotating propellers arranged along a common axis, one above the other. This arrangement reduces the area occupied by propeller discs by half. These propeller pairs are then overlapped by up to one radius. The total number of propellers and motors is the same as in the previous diagrams.



3/15/2012 6:15:50 PM f=1.50 U:\Users\dave\data\apps\EaglePCB\projects\FlyCar drawings\FluCar1\51dx27.brd

Figure 2 – 4-place vehicle, 51 x 27″ props, 150% overlap

This is far more compact and attractive model. But again, the efficiency consequences of the overlap are unclear at this time.

6 Failure mode analysis

In this section I briefly address the most common causes of accidents in conventional aircraft, and describe how the vehicle design addresses them.

6.1 Loss of power

Fixed wing airplanes can (in principle) glide to a safe landing in the event of loss of all engine power. Conventional helicopters can autorotate.

In practice power-off landings are possible only when within gliding distance of an airport (with minor exceptions for very small aircraft). Autorotation requires high pilot skill and good timing.

But the vehicle described here can do neither – without power it will fall out of the sky. Therefore instead of accepting power loss as an unlikely problem, it must be prevented completely[39].

- Mechanical failure
    - Redundant thrusters compensate for failed units
    - Automatic landing if redundancy level drops too low

- Fuel exhaustion
    - Fuel/battery reserve is automatically monitored and compared to distance/requirements to destination and safe landing zones. Vehicle will not fly beyond point of no return.

6.2 Collisions

- Flight into terrain
    - Vehicle sensors (radar, LIDAR, etc.) detect terrain and reduce approach speed automatically to avoid collision
    - On-board terrain database permits automatic path planning that avoids terrain (as well as restricted airspace, etc.)

- Flight into obstacles (wires, towers, buildings, etc.)
    - Vehicle sensors (radar, LIDAR, etc.) detect terrain and reduce approach speed automatically to avoid collision

- Mid-air collision with other aircraft
    - Vehicle sensors (radar, LIDAR, etc.) detect presence of other aircraft

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[39] I'm not sure the measures described here could cope with a EMP attack; this is worth studying, but even trains and automobiles are not safe from deliberate violent attack.

    - ATC instructions followed automatically (if delivered in machine-readable form); ATC instructions vetted for safety
    - Automatic implementation of right-of-way and flocking algorithms cause flight deviation to avoid collision
    - Vehicle location and flight path is broadcast locally (short-range) as warning and guidance to other vehicles

- Bird strikes
    - Vehicle sensors (radar, LIDAR, etc.) detect presence of birds; automatic course deviation
    - Low speed of vehicle minimizes damage from bird strikes
    - Redundant thrusters allow safe flight even after bird strike (up to a point, obviously)

6.3 Loss of control

- Vehicle inherently cannot stall or spin

- No cable linkages, control rods, pins, pulleys, hydraulics, or servos
    - No control locks to be removed before flight
    - No tail rotor
    - Control is inherently redundant; no single control surfaces
    - All control is via power modulation of redundant thrusters

- Manually piloted VFR flight into IMC can be prevented by use of sensors and online weather data
    - Visibility is not required for safe flight in automatic mode

6.4 Structural failure

- Computer-mediated control enforces Vne limits, g limits, etc.
- Overloaded vehicles will not take off
- Computer-mediated controls system enforces gentle landings, can detect excessive forces applied to vehicle (MEMS accelerometers to detect hard landing, etc.)
- Redundant thrusters permit safe flight even after some types of structural failure

7 Technical challenges

7.1 Summary

<goes here>

7.2 Noise

- Major issue

    - If unsolved, could be a show stopper, or at least a show limiter
- Electric motors are quiet compared to piston or turbine engines, but propeller noise remains
- Opportunities for phase cancellation based on large number of props?
- Active noise cancellation?
- Propeller tip speeds and Mach effects
- Propeller airfoil shapes and noise
- Ducted fans and noise
- Directing noise in particular directions (up and down, not out)
- Noise abatement navigational procedures
- Analysis needed

7.3 Thrusters

- Propellers
    - Counter-rotating pairs
    - Single vs. co-axial in-line
    - Overlap (and efficiency/noise issues)
    - Prop shape/pitch, rpm, noise, diameter
- Ducted fans
- Magnus effect
- Cyclogyro (D-DALUS) [probably not; mechanically complex]
- Other?
- Combinations
- Motor size/power/weight
- Number of thrusters

7.4 Energy storage

- Batteries
    - Li+, LiPo
    - Discharge rate
    - Future types
- Liquid fuels (see above)
    - turbines/generators
    - IC engines/generators
    - Fuel cells
- Hybrid
    - Generator/fuel cell + small LiPo batteries for emergency backup (safety)
- Exotic things
    - Flywheels
    - Nuclear (esp. RTG)
    - Beamed power
    - What else?

7.5 Control algorithms

<discuss issues here>

7.6 Redundant structures

<discuss issues here. Active sensing of stress...>

7.7 Redundant electronics

<goes here; this is a well-understood field...>

7.8 Reliability – other

- Loss of power
- Loss of propellers
- Unbalanced props
- Loss of GPS signals
- Redundant control & navigation
- Unbalanced loads
- Automatic landing
- Overload

7.9 Navigation

- Navigation in today's environment is complex; more complex tomorrow
- Today
    - ATC airspace rules
    - Separation rules
    - VFR/IFR differences
    - NOTAMs (temporary rule changes, etc.)
    - PIREPs (mostly turbulence and weather reports)
    - Existing navaids
    - Rules about automated navigation in airspace
    - Anti-collision vs. stationary ground objects
    - Anti-collision vs. other aircraft
- Tomorrow (additionally)
    - High density of similar vehicles at low altitudes
    - Flight near occupied structures
    - Noise
    - Mixing of VTOL traffic and conventional aircraft (higher speed)
    - Transition from current to future airspace models

7.9.1 Traffic/ATC

- GPS based (primary)
- Integration of no-go zones (restricted airspace, etc.)

- Integration of airspace rules (speed limits, altitudes, etc.)
- Terrain shape knowledge
- Shortest path determination
- Traffic considerations (eventually, we hope)
- ATC commands (hopefully automated)
- Traffic separation

7.9.2 Safe maneuvering

- Reliable knowledge of available vehicle maneuver capability and power/duration limits
- Anti-collision algorithms take these into account; begin braking (landing) in time to stop prior to collision (power exhaustion).
- Gradual reduction of maximum approach velocity all the way to zero closing speed at zero distance (docking, landing...)

7.9.3 Anti-collision

- Radar
- Lidar
- Acoustic/sonar
- Reference to fixed databases (terrain...)
- Reference to real-time databases
    - NOTAMs
    - Location of traffic

- Anti-collision sensor system
    - Must cope with many similar systems operating nearby. (Unique ping IDs?)
    - Must be low-power
    - Must be highly reliable (redundancy)
    - Sensor integration to form fully spherical coverage
        - Really needed? Or just in direction of travel?
    - Need distance, direction, and velocity of obstacles (or at least distance; can assume stationary for many purposes)
    - Must detect small & thin things like guy & electrical wires, thin branches, antennas, blimps, etc.

7.9.4 High density traffic issues

- Right-of-way algorithms and issues
    - In green zone
    - In yellow zone
    - In red zone
    - Red zone (at least) to have RoW priority
        - Probably NOT yellow – wrong incentives
    - See also flocking algorithms

7.9.5 Landing and parking

- We can identify safe landing zones (LZ) in a database
    - Keep it updated via wireless data
- Problem: How to know if a given LZ (=1 spot) is currently occupied by another vehicle?
    - General problem unsolved now. Needs work.
    - Workaround 1: Manual landing by pilot. [problem; what if no reserve left but no spaces left?]
    - Workaround 2: Active monitoring of each spot (local hardware). Database of currently free spots updated in real-time; reservations allowed in advance (with limits). [problem: Limited number of such spots; expense of setting up] This is probably a good solution for "powered" (charging) spots; not a solution for emergency LZs.
    - Pre-specified LZs from internal database
    - Updated via satcom or mobile data networks
    - >>> How to tell if info is up to date?
    - >>> How to tell if slot is occupied? (see above)
    - >>> Authentication & signatures

8 Short-term applications

Applications
- Recreation
- Rescue
- Police/military
- Transportation

Shorter-term:
- Regulate & license like a helicopter
- No/limited automatic modes

9 Long-term applications

9.1 Flying automated taxis

- Air taxis – shared (first widespread use)
    - Come when called on mobile
    - Priced by time
    - Charge batteries when not in use
    - Issue: No driver/pilot >> vandalism
        - ? on-board video cameras to discourage vandalism ?
        - First thing vandal will do is block/disable camera
        - Hold passenger (credit card holder) responsible for vandalism?
        - Will these work?

9.2 Privately owned flying cars

- Privately owned (first rollout as "helicopters", last rollout when ubiquitous)
    - No parking available – go away and come back when I call on mobile
    - Charge batteries when not in use

9.3 How to do long-distance travel

- Wings
    - More efficient lift than direct thrust
    - Can make vehicle's range and speed similar to conventional (electric-powered) aircraft
    - Separate models with wings?
    - Modular wings that can be stored at an airport and then attached when needed for long distance travel?
- Rapid recharge
    - Battery exchange
    - Exchange of liquid electrolytes
- Don't do it
    - Accept that this is not a long-range, high-speed vehicle; use other (conventional) aircraft for that

10 History – earlier attempts

10.1 Discussion

<Goes here; the following are my notes. Discuss the very many earlier attempts at personal air vehicles, why they all failed, and why this concept can succeed where they did not. (mostly safety, training/skill/workload, and cost issues) With pictures.>

Yesterday

- Flying cars (various) [single engine, piloting]
    - Taylor Aerocar
    - W-5 Aerobile (1936)
    - AVE Mizar (1971)
- Flying jeeps
    - Chrysler VZ-6
    - Curtiss-Wright VZ-7
    - Piasecki Model 59H AirGeep
    - Piasecki VZ-8P
- De Lackner DH-5 Aerocycle
- Hiller VZ-1 Pawnee
- Benson B-10 Propcopter
- Benson B-12 Skymat [closer]
- Rocket packs
    - Bell Aerospace Rocket Pack (~1958-1960)

- Convair XFY-1
- Lockheed XFV-1
- Moller Aircar [closer but just talk; IC engines; limited redundancy]
- Avro VZ-9-AV Avrocar

Today

- Solent AirCar
- Williams WR19/X-Jet
- Martin Jetpack
- Terrafugia [Optimized conventional design. Airports, single engine, little redundancy; same failure modes as conventional aircraft]
- NASA Puffn
- Gress Aerospace PAV
- JetLev
- LaBiche Aerospace FSC-1
- Haynes Aero Skyblazer
- Urban Aeronautics X-Hawk
- Hammerhead PAV
- Moller Skycar [see above]
- Springtail EFV-4B VTOL PAV
- Yves Rossy jet pack
- iCar 101

10.2 Why they failed

Discuss reasons. Single-point-of-failure leads to high cost (requires high quality, high maintenance, low volumes of production). Piloting skill and training. Complexity of dealing with weather, ATC, airspace rules. Navigation in pre-GPS era. Inconvenience of airports. Noise.

Discuss oddity that most (if not all) other modern proposals still retain these same problems.

10.3 What has been difficult about this problem

- Airports
    - Need for runways
    - Solution: VTOL (incl. helicopters)
- Safety
    - Pilot competence
    - Reliability requires lots of maintenance, high quality
- Cost
    - Training
    - Maintenance
    - Low-volume production

- Noise
    - May not be able to solve that now

11 Why this time will be different

- New technologies create new opportunity
    - Brushless DC motors (BDC), Li+ batteries/fuel cells/better things coming
        - Motor scale & thermodynamics
        - Unlike heat engines, BDCs do not require large size for efficiency
        - Heat engines leak heat. Must be either large (>> few) or fast (>> wear quickly) to be efficient (work before excessive heat loss). This leads to a few large heat engines – not redundant. BDMs are not heat engines; can be small & efficient. [Caveat: large props are more efficient]
    - Cheap, light high-performance computing
    - Ubiquitous mobile networks (terrestrial and satellite)
    - GPS

- New technologies allow solutions to old problems
    - No runways needed
    - No piloting skill needed
    - Safety from redundancy
    - Low costs
        - From simplicity of mechanical systems
        - Automotive (not aviation) quality components
        - Much lower maintenance & inspection costs
        - Economies of scale

12 Development path

<goes here>

- Paper studies
- Simulations
- Prototyping and testing of individual thruster units
- Construction & testing of model-sized prototypes (multiple)
- Construction & testing of single-place prototypes
    - Legally, experimental helicopters
- Full-size (2+ place) commercial prototype
- Sales of "safe" helicopters (still require licensed pilot)
    - Generate capital for further development
- Parallel work on other technical challenges
- Coordination with FAA, etc. on rule exemption, eventual longer-term airspace plan
- etc...

[end]