Aerobots as a Ubiquitous Part of Society

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Small autonomous aerial robots (aerobots) have the potential to make significant positive contributions to modern society. Aerobots of various vehicle-types – CTOL, STOL, VTOL, and even possibly LTA – will be a part of a new paradigm for the distribution of goods and services. Aerobots as a class of vehicles may test the boundaries of aircraft design. New system analysis and design tools will be required in order to account for the new technologies and design parameters/constraints for such vehicles. The analysis tools also provide new approaches to defining/assessing technology goals and objectives and the technology portfolio necessary to accomplish those goals and objectives. Using the aerobot concept as an illustrative test case, key attributes of these analysis tools are discussed.

Notation

Alt Altitude (above ground level), m
d Total distance traveled on a delivery route (d_T for a truck/automobile and d_A for an aerobot), km
D Vector/array representing the consistency of the particular individual technology with strategic technical direction guidance
e_A/e_T Ratio of aerobot energy expenditure (per kilometer traveled) over energy expended per kilometer by a truck/automobile
E Vehicle impact energy, Joules
EA_{Lim} Distributed impact energy limit, J/m^2
f Vehicle frontal area, m^2
g Gravitational constant, m/s^2
$\mathbf{G}_1$ Candidate goals matrix
$\mathbf{G}_2$ Candidate objectives matrix
I_{EP} Rotational inertia of "exposed" propulsor
K Vector/array representing the cost associated with the development/implementation of a particular individual technology (1 low to 10 high)
KE_{AF} Kinetic energy of airframe, Joules
KE_{EP} Rotational kinetic energy of "exposed" propulsor, Joules
m Aerobot "total gross weight" mass, kg
n Vehicle load factor
N_{CTjTiG} Number of contributing technologies, including j'th technology, to i'th goal
L/D Vehicle lift-to-drag ratio
PE Potential energy of vehicle, Joules
P_{ev} Probability of successful evasive maneuvers to avoid
P_F Probability of vehicle system failure that leads to significant degradation of control
P_{imp} Probability of vehicle/object flight-path conflict, subject to no evasive actions or other mitigation
P_{mit} Probability of successful impact mitigation
R_P CTOL or STOL propeller radius
R_R VTOL "lifting" rotor radius, m
q QFD-inspired technology-to-goals matrix
R Aerobot nominal range, m
S Wing planform area, m^2
T Vector/array captures institutional core competency expertise or growth interest in a particular individual technology, ranging from 0 to 10 (no to high expertise/interest)
T/W Vehicle thrust-to-weight ratio
U Vector/array representing the risk of development/implementation of a particular individual technology (1 low to 10 high)
V Vehicle horizontal velocity, m/s
V_C Cruise velocity, m/s
VROC Vertical rate of climb, m/s
V_{Stall} Stall velocity, m/s
V_{Tip} Propulsor "tip" velocity, m/s

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x Mean distance traveled (via either truck, automobile or aerobot) per package/stop, km

ε^* Normalized "elegance" metric (computational efficiency for autonomous system implementation), ranges numerically from 0-10

ϕ_{SA} Level of aerobot situational awareness impact mitigation parameter, numeric value ranges from 0-10 (low to high situational awareness)

ϕ_{SW} Level of impact mitigation stemming through human-to-machine and machine-to-machine communication and coordination (signals and warnings), 0-10 (low to high level)

ϕ_{FT} Level of flight termination impact mitigation parameter, ranges numerically from 0-10 (low to high level of protection stemming from aggregate influence of implemented fail-safe measures – i.e. parachutes, inflatable bags, treated airframe surfaces, engine cut-outs with propeller/rotor brakes, etc)

φ "Total system" predictive capability "level of fidelity," ranges from 0 to 10 (low to high)

ι^* Normalized intelligence metric, for a given level of autonomy, ranges numerically from 0-10

κ Multiplier factor accounting for probabilistic influence of evasive maneuvers and other impact mitigation measures

ρ_A Localized population density of aerobots, number of aerobots per square meter of over-flight terrain

ρ_{AC} Localized population density of aircraft flying over "aerobot inter-space" in the national airspace system (NAS), aircraft per square meter

ρ_P Localized human population density, number of people per square meter

ρ_T Property frontage "terrain clutter", number of objects (of a prescribed size), on or near the ground, per square meter

Ω Rotational speed of "exposed" propulsor, radian/s

ζ Distributed energy imparted during probable impacts, subject to probable evasive action and other mitigation, J/m^2

$\aleph$ Level of autonomy (LOA), ranges from 0-5

Introduction

THE application of robotics and autonomous system technologies to small-scale aerial vehicles is resulting in the creation of a class of devices that could be called "aerobots" (aerial robots). These aerial robots will be of many different vehicle configurations – including conventional, short, and vertical takeoff and landing (CTOL, STOL, and VTOL) platforms[1]. How are aerobots different from uninhabited aerial vehicles (UAVs)? UAVs are clearly a subset of the proposed (more general) class aerobots. However, it is intended that aerobots embody a degree of intelligence and functionality to enable more than merely autonomous flight between two given take-off and landing waypoints.

This vision of aerobots becoming an integrated part of society promises great benefits and significant challenges. This paper discusses both of these aspects of the notional aerobot paradigm. A number of notional mission requirements/profiles are outlined consistent with the overall anticipated aerobot application domain; a suite of specific aerobot concepts is provided as a result of the conceptualization process.

A modest amount of precursor developmental work has been focused on aerobots[2-3]. However, platform development alone is not sufficient. The successful widespread introduction of aerobots will dictate the definition, development, and management (distributed, not centralized) of a new type of air space, or rather "inter-space" – i.e. inter*(personal)* inter*(action)* -space. "Inter-space" for purposes of this paper is defined as being below 120 m AGL (above ground level). "Inter-space" is the air space most likely to be populated by small personal-service aerobots. The term "inter-space" is introduced to reflect the envisioned use of these small aerobots as providers of distributed personal services – which thus must interact closely with human beings just immediately above and within the environs of humans. Figure 1 graphically illustrates this vision of aerobots becoming an essential component of our society – i.e. such vehicles becoming key components of our future urban/suburban landscapes.

Fig. 1. Aerobots: small aerial vehicles providing goods (e.g. delivering a small package) and services

Central to the inter-space concept is that large numbers of aerobots will be flying over urban areas, so as to maximize their utility for the distribution of goods and services. A representative sample of the types of services and utility functions that could be potentially provided by aerobots is summarized in Table 1.

Table 1. General personal services that could be provided by Aerobots

Service Provided	Competing Service Providers	Advantages Relative to Other Providers	Disadvantages Relative to Other Providers
Utility -- small package delivery	Bike messenger, postal carrier, or automotive (car, truck, motorcycle) delivery	- Potential fuel/energy economies, as well commensurate reductions in emissions - Substantial improvements in customer service in terms of service convenience, timeliness, security, and privacy - Unprecedented provision of on-demand/just-in-time goods and services	- Public safety issues that will have to be addressed - Achieving high reliability for small aerobots - (End-to-end) system automation challenges - Public acceptance of a radically new approach to - Modest but necessary infrastructure changes
Utility -- consumable delivery (i.e. food, water, medical supplies)	Company automotive delivery or self-service personal automobile	- Small distributors/providers of specialty goods could establish a greater market base using aerobots for on-demand delivery - Greater goods/services access for shut-ins, or elderly, ill and/or disabled individuals, particularly for perishable and time-sensitive items	- Have to insure that product integrity is preserved throughout the supplier-to-consumer network, both during nominal and potentially disrupted deliveries - Insure adequate mitigation steps are taken to minimize potential for theft/misappropriation of good and services (sensitive issue when removing the immediate human presence during deliveries) - Automated end-to-end transfer/transport of perishables/consumables may be difficult to achieve
Personal or neighborhood security	On-foot neighbor watch, stationary and/or pan and tilt cameras, or private home alarm services, neighborhood patrol	- Mobility of platforms provides for enhanced persistent and/or rapid response security (tele)presence - Certain platforms could be hard to detect by intruders and/or perpetrators (e.g. small lighter-than-air (LTA) platforms with electric propulsion and dark colored envelopes for neighborhood night-watch) - Emergency services support such as local flood, mud slide, and fire watch	- Insuring privacy rights of both neighborhood/property residents/occupants -- and, legally entitled, nonresident passersby – while balancing the security demands of the public - Modest local community infrastructure would have to be developed/provided to support such "neighborhood" security services (e.g. mooring mast and helium refilling station capability for a small LTA platform)
Emergency response	Primarily police or ambulance response by automobile; under special circumstances response by manned helicopter	- On the scene emergency first responders and "Good Samaritans" are unlikely to have either the training or tools to deal with every possible emergency/contingency; rapid response aerobots with robotic and telepresence tools can be fielded rapidly upon necessity to emergency sites (e.g. an aerobot could carry a portable defibrillator to a traffic-congested site to save the life of a heart-attack victim)	- Integrated, not partial, solutions are required for this application domain; a high-performing, successful aerial vehicle design is incomplete if it is not integrated with an effective robotic- and/or telepresence-enabled emergency response kit - Possibly a large public/private infrastructure/investment would be required to realize an effective network of systems
Consumer service or entertainment (imaging and/or telepresence)	Hand-held cameras; personal travel to site of interest via various modes of transportation	- Improved professional/consumer capability for panoramic and/or other expansive imaging - Potential important archival aid in scientific studies, environmental monitoring, wildlife/forestry stewardship, and land-use management	- Safety/liability concerns - Privacy issues - Localized noise/emission issues - Potential intrusion of individual liberties onto public rights/privileges
Public safety/health	Limited (periodic, random, or in response to complaint or incident) on-site inspections by human inspectors	- Potentially enhances public safety and right-to-know/freedom-of-information data gathering - Enhance public works and public/private construction monitoring - Environmental/pest monitoring and sample gathering	- Legal questions as to when/if public agency prudent and necessary inspections using aerobots might cross-over into being perceived as unwarranted harassment - Potential for unintentional/intentional incursion into private property or business operations by nongovernmental, non-legally-mandated monitors/activists
Privacy protection	Private mobile home security alarm and countermeasures	- Active/mobile (and pervasive) security devices such as aerobots should have greater intruder deterrence/de-escalation efficacy than passive, easily negated, and/or near-invisible alternate devices - Every citizen should have access to countermeasures for every (surveillance) technology, if legally allowed; anti-bots should exist to curtail excessive and inappropriate uses of aerobots (and other intrusive devices)	- Liability/responsibility of deployment of countermeasures to protect privacy (e.g. anti-bots to block/divert away inappropriately used camera-bots) - Question of whether aerobot countermeasures could (when/how/if) unlawfully impede legally mandated agencies surveillance/pursuit of public safety/security

The above suite of personal services and utilities is consistent with earlier work[1-3,11-13,19,20,22,28]. New approaches to autonomously operate these vehicles will need to be developed, perhaps drawing upon inspiration from biology and "artificial life" computer science concepts, resulting in the definition of aerobot flight behaviors[4-10]. Additionally, there is also a need to develop innovative operational "rules of the road" to see to the realization of the aerobot/inter-space application domain. Many autonomous system technologies – both in the aerial vehicle – and on the ground suggest themselves for future development. These technology issues will be discussed further later in the paper.

Next, the main benefits and challenges are discussed for aerobots and the inter-space concept.

Aerobots & Energy Savings

One of the fundamental assumptions underlying the proposed use of aerobots for providing personal services is that they are potentially more timely and cost-effective than alternative distribution methods – i.e. ground/truck delivery. Additionally, right-sizing the means of delivery for small packages will also potentially result in reduction of air pollution. Figure 2 presents estimates of energy expenditure as a function of distance traveled for a package/stop for both a delivery truck (at two different mileages) and for a CTOL aerobot (air-dropping a package with a parachute at the mid-point of the flight). The energy expenditure for the truck includes pro-rated distance for the return of the truck to the distributor depot; one package/stop per flight for the aerobot is assumed and the aerobot energy trends include the expended energy for the vehicle return. The two trends shown for the aerobot reflect the energy expended only during cruise or, alternatively, for the total trip/delivery including the vehicle. The reason for the large constant offset between the two aerobot energy expenditure trends reflects the fraction of fuel expended on the ground or during the loiter/package drop mission profile leg. This reflects both the short hops dictated for aerobot supporting small package deliveries and the need to time on the ground engines running, as well as the need to design in methods for efficient package drops or other means of delivery. Clearly, though, the potential for substantial fuel savings exist on a head-to-head single package delivery run.

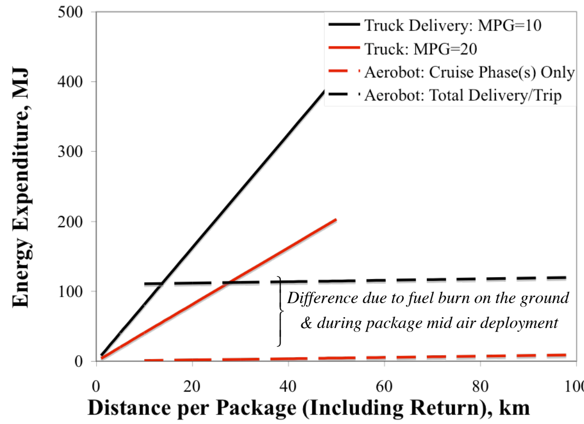
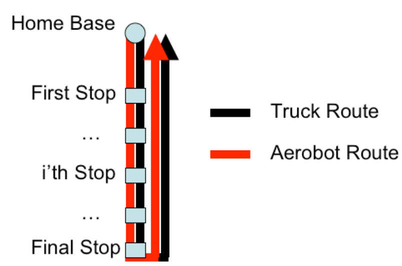
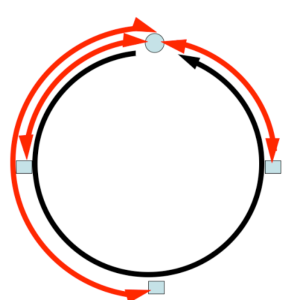


Fig. 2. Energy Expenditures (per kilometer) for Ground-Transport of Small Packages

Figure 2 only addresses part of the issue, however, as to the total energy expenditures between aerobots and ground shipping. The overall payload capacity (i.e. number of packages) and the routes taken and package distribution do have a substantial influence on possible energy savings through using aerobots for small package deliveries. Figure 3 shows for illustrative purposes three different types of routes that might be used to estimate fuel expenditure for aerobots versus automobiles/trucks: a reversed route, a closed circuit route, and direct point-to-point (for the aerobots) versus a closed circuit route (for delivery trucks).



(a)



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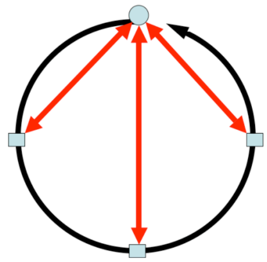


(c)

Fig. 3. Simple Delivery-Route Diagrams: (a) reversed route, (b) closed circuit route, and (c) direct point-to-point versus closed circuit

Table 2 summarizes simple expressions for the distance traveled for the Fig. 3 routes (assuming two-way traffic along all route segments), given a mean distance traveled per package/stop, x. It is assumed that an aerobot carries and delivers only one package per flight, whereas ground transport can and does carry multiple packages.

Table 2. Simple Expressions for Distance Traveled Under Certain Routes: Trucks vs. Aerobots

Truck/Automobile	Aerobot
(Linear) Reversed Route (Fig. 3a):	
$d_T = 2Nx$	$d_A = 2\sum_{n=1}^{N} nx$
(Circular) Closed-Circuit Route (Fig. 3b):	
$d_T = (N+1)x$	$d_A = 2\sum_{n=1}^{N} Int\left(\frac{n+1}{2}\right)x$
Point-to-Point (Fig. 3c):	
	$d_A = \frac{2(N+1)}{\pi}\sum_{n=1}^{N} sin\left(\frac{\pi n}{N+1}\right)x$

(1a-c)

Given the Table 2 (Eq. 1a-c) analytic expressions, Eq. 2 can be used to implicitly estimate the "breakeven" number of packages for small aerial vehicle transport versus ground shipping. (Note that this "package" breakeven relationship only considers the cruise phase of the aerobot; this relationship ignores fuel required for take-off, climb, and landing.)

$$e_A/e_T \approx d_T/d_A \quad (2)$$

Given Eqs. 1-2, Fig. 4 shows results for the breakeven number of packages above which small package transport makes sense for ground transport and not aerobot delivery, for a variety of e_A/e_T ratios.

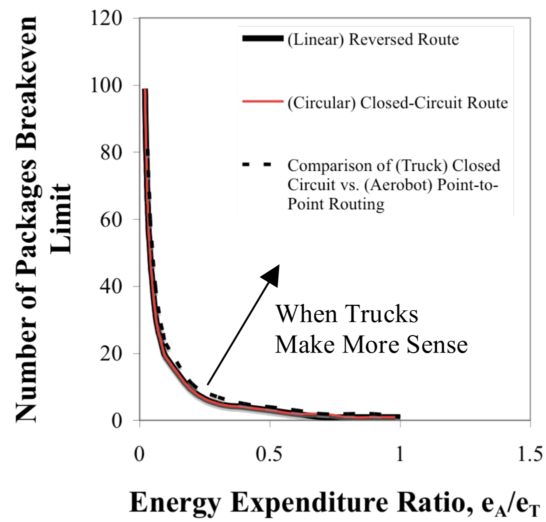


Fig. 4. Package Breakeven Trend

The notional aerobot routes shown in Fig. 3a-c are very simplistic in nature and are only shown for illustrative purposes. More robust mission/vehicle route performance analyses ultimately need to be performed, similar to the work detailed in [11-12]. For the work presented, though, there is very limited influence of the type of route followed by the aerobots/trucks that impacts the package breakeven trend. Nonetheless it is clear from Fig. 4 (from a fuel savings perspective) that aerobots should probably focus on the delivery of small, time sensitive, high-value deliveries; bulk transport of large, low value, and time insensitive goods likely should be left to shipping trucks, trains, automobiles, etc.

Aerobots & Safety

One of the inherent risks of potentially using aerobots, given their close proximity to people and other valuable physical assets, is the risk of collision. Safety is of paramount concern to the whole aerobot and inter-space concept. Efforts are underway to examine the safety implication of UAVs in the national airspace. Some of this work is also directed towards small vehicles operating out of the major airways[11-12]. Though a number of mitigating strategies can be used to maximize the safety of aerobots – particularly as to the design implications of the vehicles types employed and their relative size, weight, and kinetic energies – a key concern/challenge lies in the ability to imbue high degrees of decision-making reliability into the implementation vehicle automation and overall autonomy.

Returning to the safety implications of vehicle size, weight, and kinetic energies on collision probability and severity, some early work on this topic has been presented in the literature[14]. However, because of the unique challenges of aerobots operating in the notional inter-space, a vehicle design ground (people/property) impact "safe zone" height-velocity diagrams for aerobots will need to be defined for each vehicle configuration. It is proposed that this, perhaps, can partly be accomplished in the following manner. First, estimating the total energy of an aerobot

$$E = KE_{AF} + KE_{EP} + PE \tag{3a}$$

Where

$$KE_{AF} = \frac{1}{2} m V_C^2 \tag{3b}$$

$$KE_{EP} = \frac{1}{2} I_{EP} \Omega^2 \tag{3c}$$

$$PE = mg \cdot Alt \tag{3d}$$

(Note that the above expression for "total" energy does not include the chemical energy from residual fuel onboard the vehicle, in the event of collision. This is not considered in the analysis.)

The distributed energy, ζ, as a function of probable impacts, subject to probable evasive maneuvers and other mitigation is given by

$$\zeta = \kappa \left(\frac{E}{f} \right) P_F P_{imp} \left(1 - P_{ev}\right)\left(1 - P_{mit}\right) \tag{4}$$

P_F can be considered to be a constant; its value is dependent upon the intrinsic design and reliability characteristics of individual aerobot configurations. κ is a multiplier factor ($\kappa \le 1$) dependent upon the particular mitigation steps a particular aerobot is capable of. If no mitigation and/or evasive actions are feasible or probable then κ=1. Otherwise a functionality of the following form is suggested

$$\begin{aligned} \kappa &= k\left(P_{ev}, P_{mit}\right) \\ &\to \sum_i \alpha_i \cdot u\left(P_{ev} + P_{mit} - \beta_i\right) \end{aligned} \tag{5a}$$

Where by definition

$$\sum_i \alpha_i \le 1 \tag{5b}$$

P_{mit}, P_{ev}, and P_{imp} are functions of both aircraft design parameters, operating conditions/requirements, and sundry other vehicle/mission attributes. It might be argued (at least in the context of the current state of the art of autonomous aerial vehicles) that P_{mit} is higher if the an aerobot is under constant/direct human supervision and control and perhaps, correspondingly, has a lower value if the aerobot is completely autonomous and unsupervised, to mention just one consideration as regards impact/collision mitigation. P_{ev} and P_{imp} are not constants but functions of the general form

$$P_{ev} = f\left(n, T/W\big|_{max}, L/D\big|_{max}, Alt, V, \ldots\right) \tag{6a}$$

$$P_{imp} = g\left(Alt, \rho_P, \rho_A, \rho_{AC}, \rho_T, \ldots\right) \tag{6b}$$

$$P_{mit} = h\left(\aleph, \iota^*, \varepsilon^*, \phi_{SA}, \phi_{SW}, \phi_{FT}, \ldots\right) \tag{6c}$$

The dependence of P_{mit} on aerobot level of autonomy, $\aleph$, and the corresponding "normalized" intelligence and elegance metrics, ι^* and ε^*, draws heavily on previous system analysis and autonomy work for high-altitude long-endurance UAVs[16].

Equation 7a-c represents relatively simple models of the functional relationships of Eq. 6a-c. These simple functional forms have been used to define the notional "safe zone" curves for a given type of aerobot.

$$P_{ev} \to \left(a_0 n + a_1 T/W\big|_{max} + a_2 L/D\big|_{max}\right)\left(1 - e^{-a_3 Alt/V}\right) \tag{7a}$$

$$\begin{aligned} P_{imp} \to & \left(1 - e^{-b_0\left(\rho_P + \rho_A + \rho_T\right)}\right) e^{-b_1 Alt} \\ & + \left(1 - e^{-b_2 \rho_{AC}}\right) e^{-b_3/Alt} \end{aligned} \tag{7b}$$

$$P_{mit} \to \frac{c_1\left(\varepsilon^*\right)^{-n_1}}{c_0 + \left(\iota^*\right)^{n_0}} + c_2\left(\iota^*\right)^{n_2} + c_3\phi_{SA} + c_4\phi_{SW} + c_5\phi_{FT} \tag{7c}$$

Where $\alpha_0,\ldots, \beta_0,\ldots, a_0\ldots a_3, b_0\ldots b_3, c_0\ldots c_5$, and $n_0\ldots n_2$ are prescribed constants for the proposed models.

Given Eqs. 1-7, the resulting notional "safe-zone" diagram is illustrated as shown in Fig. 5. A small CTOL platform is assumed; no exposed propulsor is used (i.e. a turbo-fan engine, or pusher propeller, would be employed). An ad hoc approach was taken with prescribing the above noted constants and parameters for this example of a "safe zone" diagram. In particular, the failure probability was set conservatively (very) high, i.e. $P_F = 0.1$ – lower values would result in significantly increasing the velocity-height envelope. The parameters used to generate the Fig. 5 diagram are as follows: m = 10 kg; $EA_{Lim} = 1600$ J/m^2; f = 0.02 m^2; N = 2.5; $T/W_{Max} = 0.25$; $L/D_{Max} = 10$; $\aleph = 4$; $\iota^* = 4$; $\varepsilon^* = 7$; $\phi_{SA} = \phi_{SW} = \phi_{FT} = 7$; $\rho_A = \rho_{AC} = \rho_P = \rho_T = 0.001$ 1/m^2. The prescribed constants used in the "safe-zone" model are correspondingly: $a_0 = a_1 = a_2 = 0.05$; $a_3 = 5$; $b_0 = b_2 = b_3 = 100$; $b_1 = 0.01$; $c_0 = c_1 = 1$ and $c_2 = 0.005$ (values consistent with [16]); $c_3 = c_4 = c_5 = 0.02$; $n_0 = n_1 = n_2 = 1$; $\alpha_0 = 0.25$; $\alpha_1 = 0.5$; $\alpha_2 = 0.25$; $\beta_0 = 0.75$; $\beta_1 = 0.25$; $\beta_2 = 0.01$. Note that the stall boundary for the CTOL aerobots and the "deadman" curve boundaries for VTOL platforms should also be superimposed in "safe-zone" diagrams. These curves account for approximate relative velocities and kinetic energies of common "projectile" impacts encountered in sport and other similar endeavors[23]. These "safe zone" curves, however, are notional only and should not be construed as an actual endorsement -- regulatory or otherwise --of the relative safety of aerobots or any other "projectile." Such an exercise is well outside the scope -- and purview – of this paper.

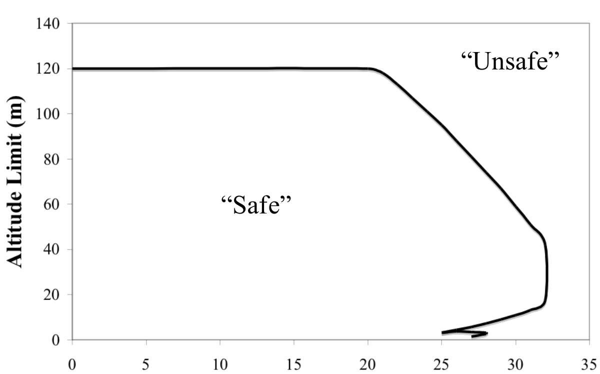


Fig. 5. Notional "Safe Zone" Height-Velocity Diagram (for CTOL platform)

Concluding this discussion, the above functional relationships, which incorporate both mission requirement and vehicle design parameters, suggest an approach by which the prevention/mitigation of ground/air collisions for aerobots (or UAVs or aircraft of other types) can potentially be integrated into the aircraft design process.

There are four basic methods of delivery that present themselves for small package delivery applications: (a) VTOL, (b) STOL, (c) parachute air-deployment from CTOL, and (d) tether-deployment from a lighter-than-air (LTA) platform. Other vehicle configurations are also briefly discussed in the context of other personal service applications.

From an aircraft design/technology perspective, major elements of the proposed aerobot/inter-space concept are currently demonstrable – it is only a question of making such a system sufficiently reliable, safe, and cost-effective enough to enable consumer confidence to make it a viable alternative to other personal service approaches/providers.

A Potential Aerobot Aviary

The complementary concepts of inter-space and aerobots intrinsically imply a certain underlying element of bio-inspiration in their conception. After all, ideally aerobots should just as safely and efficiently coexist and interact within people's environment as the birds. This bio-inspiration is anticipated to carry over into more meaningful technological manifestations – particularly in the form of vehicle flight control and behaviors (for aerobot coordination, collision avoidance, and overall navigation) and the overall inter-space "rules of the road," so to speak. Even the anticipated diversity of vehicle types/sizes and functions implies a sort of aerobot ecology[3].

A representative number of aerobots -- with distinct behaviors, mission roles, and speed/altitude "eco-system" niches -- will now be discussed in the context of aerial vehicle design requirements. Among these different aerobot types are: 1. home delivery hauler, 2. courier-bots (both mail and small packages), 3. pizza delivery flyers, 4. police-bots (replaces manned helicopter police surveillance of city), 5. security-bots (home and neighborhood security), 6. emergency-bots (provides emergency medical and accident/disaster support), 7. anti-bots (robotic deterrent to protect privacy, i.e. blockades and perhaps terminates non-approved aerobots encroaching in private-space), 8. camera-bots (personal flying digital cameras), and 9. eco-bots for environmental sampling. This is, of course, hardly an exhaustive (or necessarily practical) list for aerobot missions, but it reflects a broad spectrum of notional capabilities.

Table 3. Representative Aerobot Types & Their General Characteristics

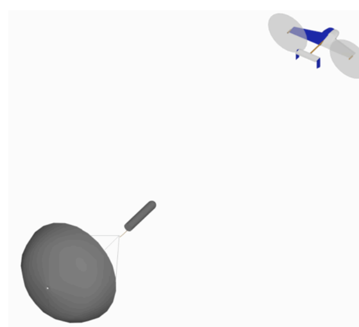
Name	Range or Loiter	Payload	TOL Distance	Rate of Climb	Min/Stall Speed	Cruise Speed	Load Factor
Home Delivery Hauler	>30 km	>10 kg	<100 m	>150 m/min	>60 kph	>100 kph (kilometers per hour)	<+2.0 g
Courier-Bots	>50 km	>2 kg	<100 m	>150 m/min	>60 kph	>100 kph	<+2.0 g
Pizza Delivery Flyer	<10 km	>2 kg	<20 m	>150 m/min	<25 kph	>60 kph	<+2.0 g
Police-Bot	>50 km with 0.5 hr loiter	>50 kg	<100 m	>300 m/min	<25 kph	>200 kph	<+10 g
Security-Bot	>2 hr	>5 kg	<20 m	>50 m/min	<25 kph	<40 kph	<2.5 g
Emergency-Bot	>50 km with 0.5 hr loiter	>150 kg	VTOL required plus ground-deployment & retrieval of medical telepresence/robotic payload/device	>300 m/min	0	>200 kph	<+10 g
Anti-Bot	>0.2 hr	>0.1 kg	VTOL required	>50 m/min	0	<40 kph	<+1.2 g
Camera-Bots	<0.5 hr	>0.5 kg	<20 m	>50 m/min	<25 kph	<40 kph	<+1.2 g
Eco-Bots	>2 hr	>1 kg	VTOL required plus limited surface mobility/manipulation	>50 m/min	0	>60 kph	<+1.2 g

The Table 3 mission/function requirements are, of course, conjectural. The intent is to elicit a large diverse set of new concepts and emerging technologies, the design parameter information derived from this suite of concepts will be used in the context of subsequent conceptualization and technology portfolio discussion.

Notional mission requirements, conceptual designs with first-order sizing, and general autonomous capability discussion will now be summarized for the above-noted sample list of aerobot types. This work seeks to accomplish the objective of illustrating the power of the paradigm of "aerobots as a ubiquitous part of society."

Home Delivery Hauler

Two different notional concepts are illustrated in Fig. 6 for the small package home delivery application: a fixed-wing CTOL aerial platform with parachute aerial deployment of the packages and a conventional (though small-scale) single-main rotor/tail-rotor helicopter VTOL option.


(a)

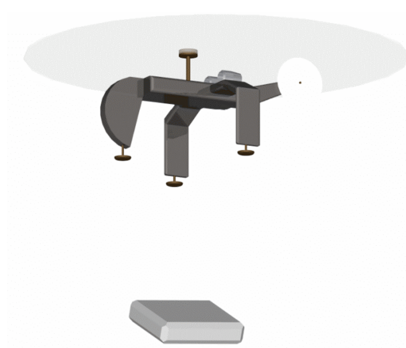

(b)

Fig. 6. Home Delivery Hauler: (a) fixed-wing platform with parachute deployment of payload and (b) rotary-wing platform

A notional mission profile for a CTOL "Home Delivery Hauler" platform is shown in Fig. 7. This mission profile, and the associated requirements shown in Table 3, was used for first-order sizing/conceptual design analyses.

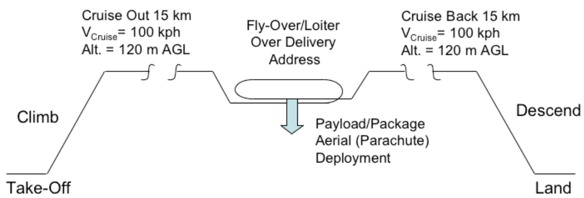


Fig. 7. Notional Mission profile for the CTOL version of the "Home Delivery Hauler"

For the CTOL configuration, a first-order conceptual design methodology based on [24] was used to perform vehicle sizing and performance estimates. However, in order to perform such analysis for small aerial vehicles, particularly for UAVs, it was necessary to apply appropriate correction factors to the basic [24] methodology. Using vehicle data from [25, 33], a correction factor expression (Eq. 8a-b) was derived to adjust the vehicle empty weight fraction estimates. This empty weight correction factor expression is a function of vehicle takeoff gross weight, W_0 (in units of N); the constants a = 0.6826 and b = 0.000527 (or b = 1/1898) were found using regression analysis.

$$\left.\frac{W_e}{W_0}\right|_C = C_{F_{Eng}} \cdot \left.\frac{W_e}{W_0}\right|_U \quad (8a)$$

$$C_{F_{Eng}} = 1 - ae^{-bW_0} \quad (8b)$$

Results from this empty weight fraction correction factor regression analysis are summarized in Fig. 8. As can be seen, the required correction factor has a significant influence on the empty weight fraction estimates – particularly for very small aerial platforms. For nominally RC (radio-controlled) model airplane class vehicles, the correction factor when applied to the [24] weight equation yields empty weight fractions approximately one-third of otherwise "un-corrected" estimates.

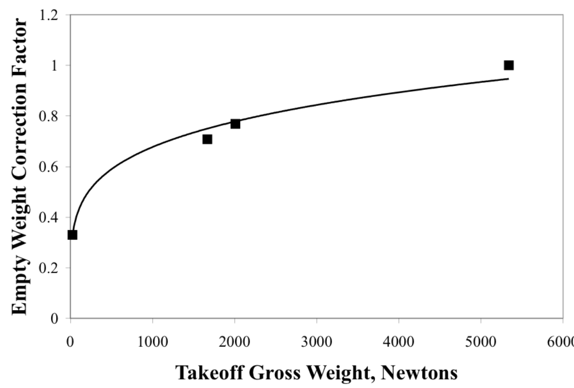


Fig. 8. Small Aerial Vehicle Empty Weight Correction Factors

Another extension adaptation of the [24] sizing methodology is the dealing with the estimation of uninstalled avionics and, in the case of autonomous aerial vehicles, the mission/flight computer(s) and associated intelligent system hardware required to implement/embody the needed vehicle autonomy. Earlier work [36] tackled this issue, in a very preliminary sense, with regards to autonomous (planetary) aerial vehicles; the [36] weight equation for mission/flight computer(s) and other avionics components was used for the aerobot estimates noted in this paper. This equation, slightly modified, is given again below

$$\begin{aligned} m_{MC\&Av} = {} & \mathrm{u}(20 - m_{GW})[a + b\,\mathrm{u}(m_{GW} - 5) + c\,\mathrm{u}(m_{GW} - 10)] \\ & + d m_{GW}\,\mathrm{u}(m_{GW} - 20) \end{aligned} \quad (9)$$

Note that the u(x-x_0) is the step-function; for x≥x0 then u(x-x_0) = 1 for x<x0 then u(x-x_0) = 0. Further, a = 0.09 (fixed weight that provides for radio receiver and basic trim mixer circuit board capability). An onboard camera will be required for somewhat larger (operational versus proof-of-concept vehicles), and so b=0.109. To add an autopilot and mission computer (PC-104 single-board computer), c=0.08. Maximum assumed fixed weight of mission computer, avionics, and guidance/navigation sensors (with redundancy), gives d=0.1. Finally, m_{GW} denotes the mass associated to the take-off gross weight of the vehicle, i.e. $m_{GW} = W_0/g$. Obviously, as new technology is injected in mission/flight computer and avionics components (in the form of further miniaturization, fault-tolerant/redundant systems, and advanced sensors/instruments), the above weight equation constants and step function thresholds will need to be adjusted to reflect the technological advances.

Table 4 summarizes the topmost results of the first-order sizing/performance estimates made for the "home delivery hauler" aerobot, subject to the notional mission requirements noted in Table 3. The analysis was performed with "rubber engine" sizing for piston-engine propulsion.

Table 4. CTOL-version of the "Home Delivery Hauler" Aerobot

Dimensions	
Wing Span	2.56 m
Wing planform area	0.84 m^2
Wing aspect ratio	7.8
Wetted area ratio, S_{wet}/S_{ref}	4.8
Vertical tail area	0.18 m^2
Horizontal tail area	0.29 m^2
Fuselage length	1.37 m
Fuselage fineness ratio	3.86
(Dual) Propeller radius (3 bladed)	0.32 m
Weights	
Gross weight	23.8 kg
Empty weight fraction	0.462
Fuel weight fraction	0.105
Payload weight fraction	0.433
Aero/Performance Characteristics	
Wing loading	278 N/m^2
Propeller/propulsor power loading	4.6kg/kW
Max lift coefficient (w. plain flaps)	1.71
Cruise lift-to-drag ratio (pre-delivery)	14.8
Wing Reynolds number (based on MAC)	6.6x10^5
Parasite drag coefficient	0.022

The size/performance characteristics of the CTOL version of the "Home Delivery Hauler noted above is in good agreement with CTOL UAVs in the 150 kg (and under) class of vehicles. It is particularly important, though, to point out the relatively small fuel weight fraction for this and most of the other aerobots. This principally reflects the short "hops" that aerobots are notionally anticipated to make performing small package deliveries. As noted earlier in the paper (Fig. 2), if vehicle deployment from mercantile/commercial depots are not carefully thought out -- and automated as much as possible to minimize flight delays -- then most of the fuel burned could be on the ground, rather than in the air.

The notional mission profile for a VTOL, or rotary-wing, version of a "Home Delivery Hauler" is shown in Fig. 9. It is important to reiterate that the intent for proposing this large diverse suite of vehicle concepts is not to engage in some form of "analysis of alternates" effort, but rather to define a robust portfolio of potential technologies to explore.

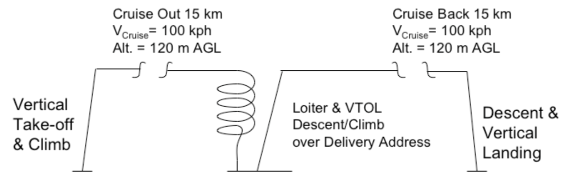


Fig. 9. Notional Mission profile for the VTOL or Rotary-Wing version of the "Home Delivery Hauler"

A production rotary-wing UAV that is approximately in the same general class of vehicle (in terms of gross weight, payload capacity, endurance, etc) as the notional rotary-wing version of the "home delivery hauler" is the Yamaha RMAX[19].

Courier-Bots

The courier-bot application is notionally very similar to the small home delivery application. The key difference between the two applications is the somewhat higher speed and range requirement for the courier-bot (reflecting the smaller and more select pool – but geographically more sparse and distributed – service providers and customers of this type of service). Because of the comparatively higher speed and range requirements of the courier-bot, Fig. 10 shows a CTOL platform (with an air-deployed courier package/pod) based on jet engine versus propeller propulsion. Though propeller propulsion is far more common currently for small aerial platforms, small turbojet units are becoming readily available[34] and being used to power some very large "RC model airplanes" (some with wing spans on the order of 4 to 6 m).

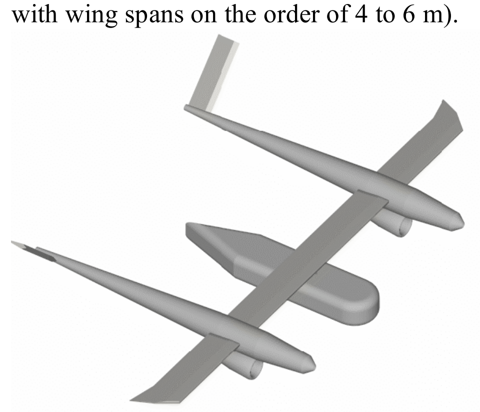


Fig. 10. Courier-Bots

Table 5 summarizes the sizing/performance analysis results for a (single) propeller-driven courier-bot CTOL configuration, based on the Table 3 notional mission requirements. It is assumed that the payload/delivery package would be air-deployed by steerable parachute from an aft clamshell-type door from the (single hull) fuselage.

Table 5. Single Tractor Propeller-Driven "Courier-Bot"

Dimensions	
Wing Span	2.06 m
Wing planform area	0.57 m^2
Wing aspect ratio	7.5
Wetted area ratio, S_{wet}/S_{ref}	4.0
Vertical tail area	0.155 m^2
Horizontal tail area	0.251 m^2
Fuselage length	0.88 m
Fuselage fineness ratio	9.9
(Single Tractor) Propeller radius	0.242 m
Weights	
Gross weight	7.7 kg
Empty weight fraction	0.643
Fuel weight fraction	0.108
Payload weight fraction	0.249
Aero/Performance Characteristics	
Wing loading	133 N/m^2
Propeller/propulsor power loading	4.6kg/kW
Max lift coefficient (no high-lift)	0.81
Cruise lift-to-drag ratio (pre-delivery)	10.6
Wing Reynolds number (based on MAC)	5.55×10^5
Parasite drag coefficient	0.022

Reference [24] provides a "rubber engine" power-law expression (based on statistical analysis of empirical data) for jet engine propulsors. It was necessary to calibrate/correct the power-law expression (derived from data for larger jet engines) to make accurate engine sizing estimates for small turbines. Using a limited set of manufacturer (refer to [34]) data, a correction factor expression (Eq. 10a-b) – in terms of engine maximum thrust rating – was derived through regression analysis. The correction factor is in terms of T_{Max}, which is the maximum turbine thrust output (in units of N); the constants for the expression are a = 4.5873 and b = 0.0375 (or b ≈ 1/27).

$$W_{Eng}\Big|_C = C_{F_{Eng}} \cdot W_{Eng}\Big|_U \quad (10a)$$

$$C_{F_{Eng}} = 1 + ae^{-bT_{Max}} \quad (10b)$$

Figure 11 illustrates the original small turbine data set as well as the resulting correction factor curve fit. Fairly good agreement was achieved for a fairly small data set. This correction factor analysis was incorporated into the sizing/conceptual design analysis of the "courier-bot" jet engine concept variant. Additionally, manufacturer-cited specific fuel consumption (SFC) values ranged from 1.3 to 2.0 hr^{-1} (much greater than values cited in [24] for larger jet engines). A small turbine SFC value of 2.0 hr^{-1} was used in the courier-bot performance analysis for conservatism.

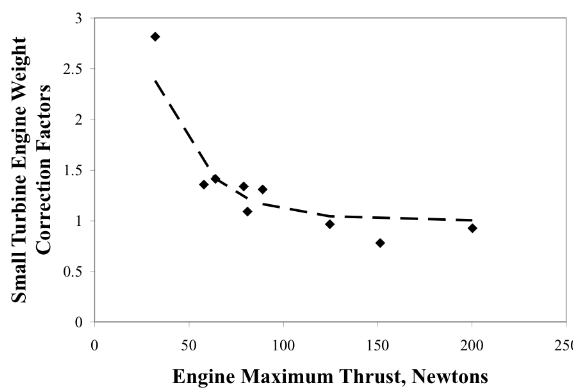


Fig. 11. Small turbine correction factor results

Table 6 summarizes the courier-bot sizing and performance analysis for a CTOL jet-engine-propelled configuration. It is assumed that twin jet engines propel a multi-fuselage (a trimaran, or three hull) CTOL configuration. The middle hull/fuselage is a payload "pod" that would separate in mid-flight, over the delivery target, from the rest of the aircraft. Therefore this trimaran vehicle configuration would have two distinct airframe configurations during the cruise phase pre- and post-delivery of the payload/delivery package. This is reflected principally in the wetted area ratio for the two cruise phases (S_{wet}/S_{ref} = 7 for the pre-delivery phase and S_{wet}/S_{ref} = 5 for the post-delivery/return-to-depot phase). This multi-fuselage aircraft configuration has similarities with Rutan's "White Knight" carrier aircraft[39].

Table 6. Twin Jet Engine, Multi-Fuselage "Courier-Bot"

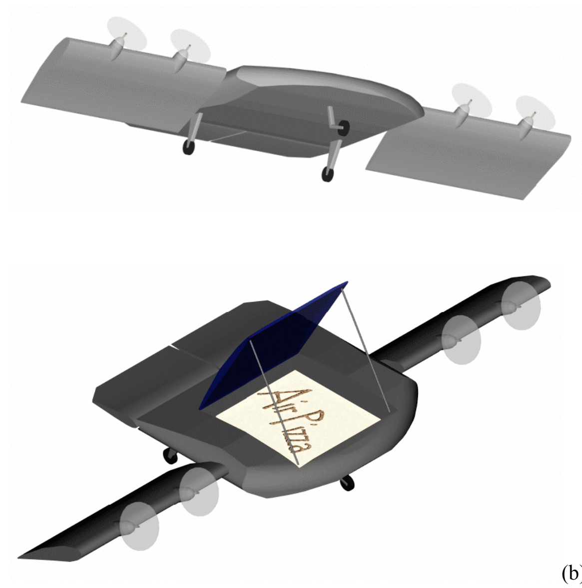
Dimensions	
Wing Span	1.63 m
Wing planform area	0.354 m^2
Wing aspect ratio	7.5
Wetted area ratio, S_{wet}/S_{ref}	5.68
Vertical tail area	0.164 m^2
Horizontal tail area	0.257 m^2
Fuselage length	0.58 m
Fineness ratio (two outermost hulls)	6.5
(Twin) Jet engine max thrust rating	5.4 N
Weights	
Gross weight	5.5 kg
Empty weight fraction	0.365
Fuel weight fraction	0.242
Payload weight fraction	0.393
Aero/Performance Characteristics	
Wing loading	152 N/m^2
Jet engine max thrust-to-weight ratio	0.2
Max lift coefficient (no high lift)	0.81
Cruise lift-to-drag ratio (pre-delivery)	7.49
Wing Reynolds number (based on MAC)	4.39×10^5
Parasite drag coefficient	0.033

An interesting aside as to the post-delivery cruise phase (return to base), is not only does the payload "drop" in terms of vehicle weight have to be accounted for in the lift-to-drag estimate, but the reduction in wetted area as well, after the payload "pod" has also been dropped off. This results in an approximately 25% reduction in wetted area for the flight back to base. Finally, as can be noted in Tables 5 and 6, the ratios of wing-span to fuselage-length are quite large by conventional aircraft standards; to preserve good longitudinal static stability characteristics, the use of tail boom extensions beyond the fuselage mold lines (as seen in several CTOL UAV designs) may be required to be added to the aerobot designs.

Pizza Delivery Flyer

Does the world really want or need a small aerial vehicle to deliver pizza – in place of the uncounted numbers of automobiles and trucks currently being used for delivery? That will remain an unanswered question for the future. One thing is certain though the development of such vehicles would make for exciting and inspiring design, build, and fly student design competitions.

One notional approach from a vehicle configuration perspective for the "Pizza Delivery Flyer" is a combination blended-wing-body and tilt-wing aircraft to yield a large volumetric payload capacity in an airframe configuration optimized for STOL capability for residential street take-off and landing.



(a) (b)

Fig. 12. Pizza Delivery Flyer: (a) STOL landing and (b) delivery

Police-Bot

Essential attributes of a notional police-bot are hovering capability, quick low-speed maneuverability, high acceleration and dash speeds, and small size so as to be difficult to target by hostile criminal suspects. In many regards these requirements evoke hummingbird-like bio-inspiration for the police-bot.

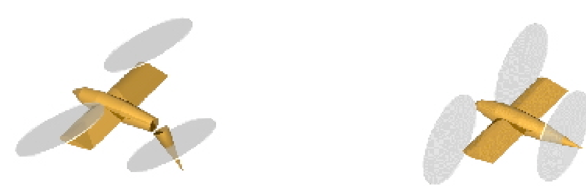


Fig. 13. Police-Bot

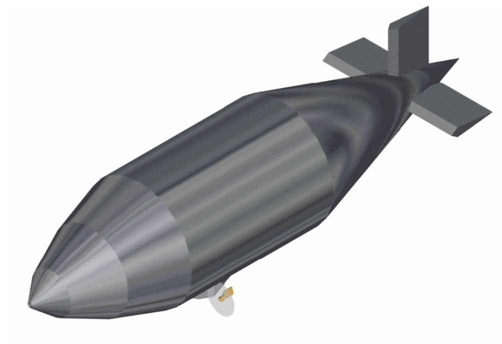
The notional vehicle shown in Fig. 13 is a hybrid of tilt-wing/convertible aircraft that, in addition to the two propellers on the tilting wing, also has a tilting propulsor mounted on the tail-boom/empennage that converts to a pusher-propeller in cruise. It requires proportionally long landing gear, that are likely retractable, to provide ground clearance for the rear tilting propulsor during take-off and landing. (Alternatively, a non-rotating inner static mast could be used for the rear tilting propulsor to provide overall rotor mast stiffness as well as acting as a tail gear when on the ground.)

The torque between the two forward/wing-mounted propellers is counterbalanced by each other, as they are counter-rotating. Differential nacelle tilt between the two wing-mounted propellers would be used to counterbalance the torque of the aft/empennage-mounted propeller, in hover and low-speed flight. The differential nacelle tilt is zeroed out as the mean nacelle tilt angle is commanded to zero. Subsequently, in airplane-mode, the torque from the aft/empennage-mounted pusher-propeller would have to be trimmed out by ailerons.

This general configuration (with tilting aft/empennage-mounted pusher-proprotors) is similar attributes to the Augusta A119 concept, proposed/studied circa 1961 [42].

Security-Bot

Already government and corporate organizations are emplacing large numbers of surveillance and security systems (especially fixed-base video cameras) in public and private areas in the hopes of improving safety, security, and privacy. It is a logical extrapolation of current trends to anticipate that mobile aerobots will be called upon to perform similar functions in the near future. Such vehicles would also be good for temporary security monitoring requirements – e.g. for the Olympics, parades, sporting events, etc. Aerial mobility, with on-demand station-keeping/routing, would provide a powerful enhancement for security. From a vehicle autonomy perspective, technology efforts are already underway to develop such up close-in surveillance capability[19].



(a)

(b)

Fig. 14. Security-Bot: (a) LTA airship and (b) rotary-wing platform

Figure 15 illustrates a representative empirical sizing trend for small outdoor radio-controlled airships. This trend is based upon a set of manufacturer data from several vendors. Autonomous airship-based aerobots are anticipated to have similar sizing/performance characteristics. Neighborhood crime-watch-type surveillance is likely to be a viable application for such platforms.

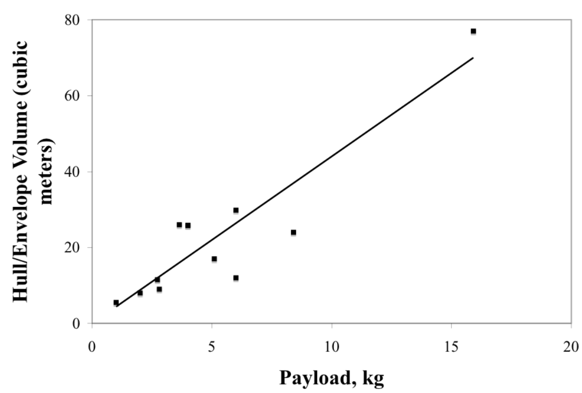


Fig. 15. Representative Sizing Trend for Small Outdoor Radio-Controlled Airships

The observed trend for small airship is roughly linear with respect to hull/envelope volume as a function of payload mass to be carried. This linear trend has the approximate slope of a=4.4, as derived from a limited number of manufacturer-provided data sets.

$$Vol_{Envelope} = aW_{Payload} \tag{11}$$

Therefore, in order to meet the Table 3 security-bot mission requirement of a 5 kg, or greater, payload capacity, a small LTA/airship (given Eq. 11) performing that role would have to have a minimum hull/envelope volume of 22 m^3. Assuming a fineness ratio (length to maximum diameter) of three, and a roughly ellipsoidal shaped hull, the corresponding hull length would be 11.5 m. These overall dimensions, and required payload capacity, are well within the current state-of-the-art for small (radio-controlled) airships.

Maximum velocities for small airships likely would range between 37 to 55 km/hr (based on manufacturer data for current systems). This would place the required cruise speed of the security-bot within, but at the high-end, of small airship speed capabilities. Small airship handling in gusts and high winds is problematic, though, and their usage/applications should be tempered by this consideration. Nonetheless, small autonomous airships would be perhaps the perfect embodiment of the low kinetic/potential energy (maximum "safe zone") aerobot. Deployable tethers could be used in conjunction with these small airships to provide them a degree of surface interaction capability.

Emergency-bot

The emergency-bot is a clear example of where hybrid autonomous system (and robotic) elements have to be successfully melded/married together in order to accomplish the anticipated missions for this class of vehicle/system. A key consideration in the development of emergency-bots would be the total system integration of the aerobot with robotic/tele-operated devices (with self-deployment from the aerobot and inherent ground mobility to reach victims/responders or, alternatively, manually transported by first responders and/or good Samaritans). One example of such a semi-automated emergency kit is the portable defibrillator. Alternate examples could include: specialized listening devices for locating earthquake or mud slide victims; respirators, oxygen tanks, and heat-blankets/protective-gear for victims of grass/forest fire. Such a robotic "symbiosis" is essential for this mission/application domain. Aerobot design would, by necessity, be heavily influenced by this symbiosis.

Speed, range, and payload capacity have to be maximized for the given vehicle gross weight category. Finally, the ability to hover, land, and take-off from uncertain/unknown landing areas (likely a cluttered environment with objects, debris, and victims/first-responders) is also a key requirement. The vehicle concept shown in Fig. 16 is a pusher-proprotor-type tiltrotor aircraft. This platform stems from an old concept – the best-known example is the Focke-Achgelis FA 269 (which underwent small-scale testing but nothing further, circa 1938-1942)[37]. Pusher-proprotor tiltrotor aircraft potentially promises a lightweight, low-drag, whirl-flutter-resistant design alternate to conventional tractor-type tiltrotor aircraft.

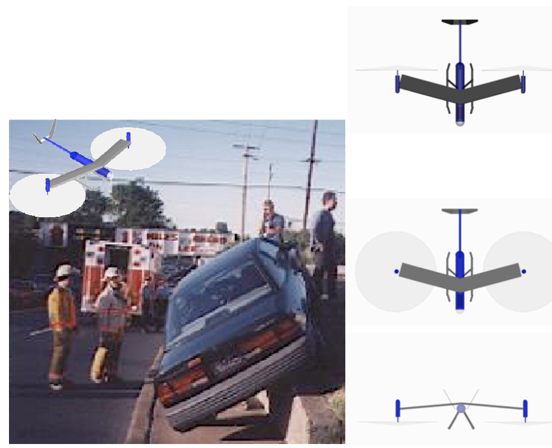


Fig. 16. Emergency-bot: (a) responding to a typical public service emergency scenario and (b) general layout

A near-production aerial vehicle having similar attributes as the above notional emergency-bot is the Bell Helicopter Textron "Eagle Eye" tiltrotor UAV[38].

Anti-Bot

Home- and/or property-owner privacy and security considerations in the face of aerobot infusion into society will likely dictate the corresponding development of measures to restrict and/or constrain the use of such aerobots.

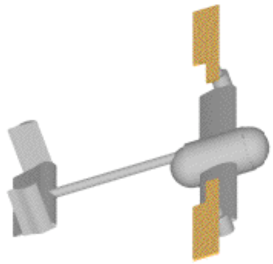


Fig. 17. Bio-inspired "Anti-Bot"

A notional anti-bot mission profile is shown in Fig. 18. The vehicle would be small, lightweight, and likely use electric-propulsion. It would loiter, land/recharge, and fly again repeatedly. It would rotate in and out of duty with other anti-bots to maximize overall aerial coverage. It would be constantly vigilant for possible ground or aerial intruders that infringe upon property-owners privacy.

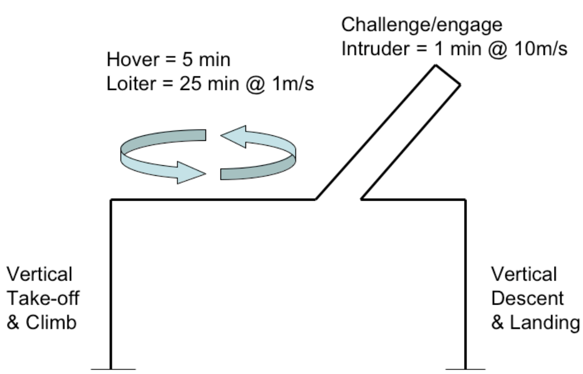


Fig. 18. Notional Mission Profile for Anti-Bot: Protecting Property Owner Privacy and Security

Biological inspiration is reflected in the particular anti-bot configuration shown in Fig. 17 in that it is a hybrid rotary/flapping-wing platform. Figure 19 highlights the rotor sizing tradeoffs inherent with the hybrid concept; as wing flapping provides more thrust less thrust is required from the rotors and, therefore, less rotor disk area.

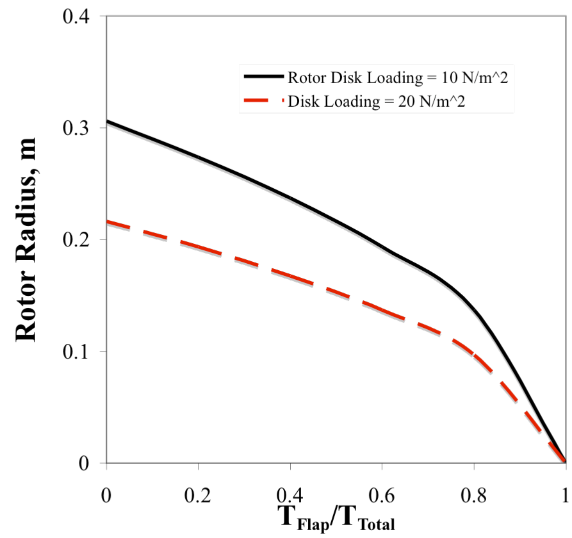


Fig. 19. Trade between Rotor Size and Flapping Wing Thrust Contribution for Hybrid Vehicles

Camera-Bots

The motion-picture industry is already in the early stages of embracing "camera-bots" for difficult location aerial shots for movies.

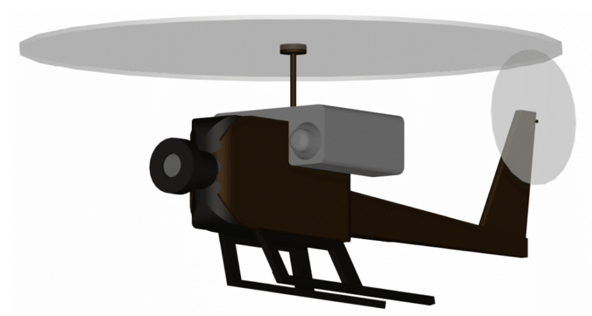


Fig. 20. Camera-Bots

Several one-of-a-kind small aerial platforms have been developed and used to provide low-cost aerial cinematography to support movie-industry cinematography, architectural and archaeological surveys[40-41]. Maturation and migration of this technology, in the near-term future, to the high-end consumer electronics market is entirely plausible.

Eco-bots

This type of aerobot application requires a strong coupling of aerial mobility with "surface interactive" task performance capability.

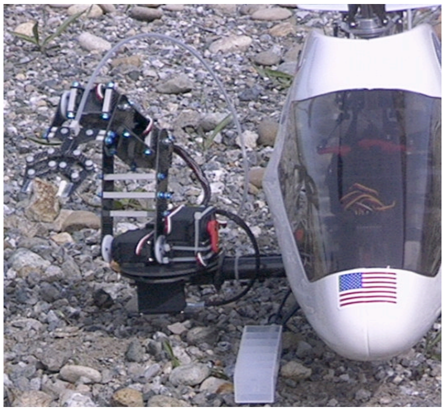


Fig. 21. Eco-bots

The coupling of rotary-wing aerial mobility with surface interactive capability has seen some limited realization to date in research prototypes[21-22]. An interesting complementary study of the eco-bot concept is being performed for possible orchard frost protection applications[20].

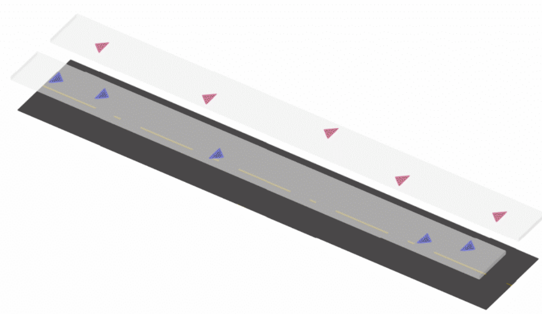
Aerobot "Rules of the Road" & Bio-Inspired Flight Control

It obvious from safety considerations alone, that new flight control and coordination concepts would have to be developed for aerobots versus conventional aircraft. In this regards, the concept of inter-space would tightly marry surface (automotive) traffic concepts with aerobot flight control. Therefore, it is anticipated that certain "rules of the road" for aerobots need to be defined; consequently, such "rules of the road" will have attendant implications for required aerobot autonomous system technologies, as well as implications for the vehicle physical design itself (for example, vehicle mass, speed, and altitude will also have to account for impact/collision mitigation, as discussed earlier in the paper).

Inter-space is anticipated to have multiple zones of operation for aerobots. Individual aerobot types will be constrained to operate in one given zone most of the time. In between zones there is assumed to be "transition layers" used on a temporary basis for passing slower aerobots or crossing under or over the flights path of aerobots flying at orthogonal or oblique angles with each other. This is analogous to passing or turn lanes for automobiles. The net effect of this is achieving a sort of "roadways in the sky" paradigm for inter-space vehicle navigation, collision avoidance, and overall flight control.

Previous work on autonomous aerial vehicle flight behaviors [4, 5, 6, 15] can be coupled with "artificial life" work into "boids" [7-10] to yield possible solutions having applicability to the aerobot/inter-space flight control problem. The aggregate of "boid" flocking rules coupled with the above aerobot "rules of the road" can be incorporated/embodied into emotional holon "anxieties" and flight behaviors as represented by an aerial vehicle bio-inspired autonomy architecture [15].

Figure 22 notionally illustrates the some of the challenges inherent in devising such rules of road for aerobots operating in inter-space. If for example, as suggested, aerobots primarily fly over existing surface roadways so as to minimize perceptions of diminished safety and privacy, then there are clear questions as to how to effect that surface-road-following without undue hazard avoidance challenges. I.e., how can one analogously mimic traffic behaviors such as intersection crossings, left turns across traffic, etc? This issue is especially challenging in terms of automated precision flight and the inability for CTOL/STOL aircraft, at least, to stop, "pullover," or "backup."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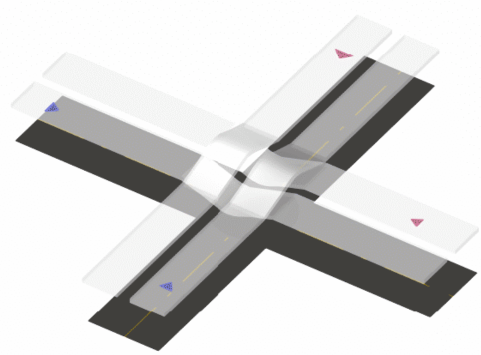
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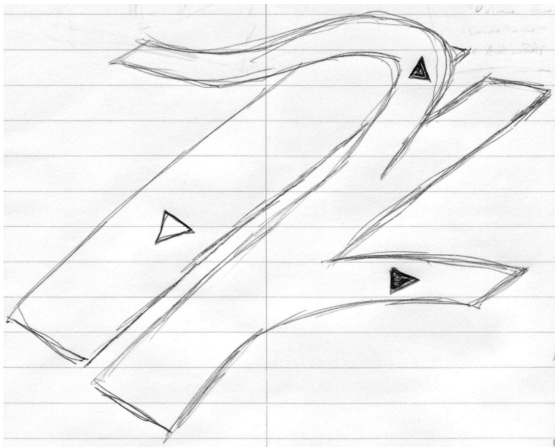

(c)

Fig. 22. "Inter-space" and aerobot "rules of the road:" (a) following surface roadways, (b) "intersections"/intersecting flight paths and (c) making "left turns" over and past parallel opposing aerial traffic

Even with the above proposition that aerobots flying through inter-space would have flight paths that are heavily surface-roadway dependent, it might be perhaps feasible for aerobots at the upper boundary (altitude) of inter-space to follow a more direct linear point A to point B flight path, therefore the tracking with respect to surface-roadway congruent waypoints could be "relaxed," refer to Fig. 23.

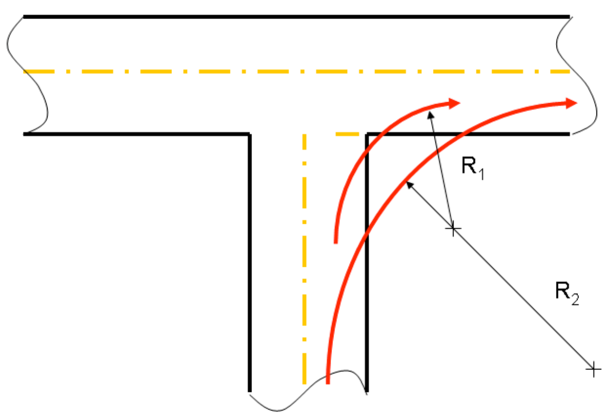

Fig. 23. Relaxation Factor (wherein the turn radius R_1 is "relaxed" to R_2) related to tolerance of waypoint tracking (and over-flight of roadways versus adjacent properties)

A Total System Perspective

Beyond the aircraft design, flight control, and operational challenges, a total system approach is required for the adoption of the complementary inter-space and aerobot concepts. The holistic aspects of this systems approach include not only aircraft design issues/technologies but the development of complementary robotic/automated "symbiotic" systems as well (refer to Table 7). Additionally, this total system approach also has to address operational (how to safely fly in close proximity to other aerobots, people, and property) and architectural issues (such as modifications/evolution of residential/business property building design layouts and auxiliary systems). Only in this manner can the combination of the aerobot and inter-space concepts reach their fullest realization.

CTOL/STOL aerobots might be required to take off and land on residential streets. Obviously this is only performed to date by conventional manned general aviation aircraft in only the direst emergency situations. (Note that ground taxiing to residential/business frontage parking strips might also be required.) An alternate CTOL approach is the use of micro-parachute/air-deployed packages over designated areas. Past work has already shown how such systems could be incorporated into aerobot systems[3]. There is also ongoing research activity examining the development of autonomous steerable parachutes for military applications which be transitioned to civilian/commercial applications[17-18]. VTOL aerobots, on the other hand, can take off and land on entranceways, parking strips, lawns, and sidewalks, as need be.

Constraints on the inter-space paradigm include buildings, landscaping, and conventional aircraft and restricted air spaces, and integration of aerobot aerial traffic with automotive and pedestrian ground traffic (operating out of residential districts). From a residential architectural perspective, future residences/homes might convert, and/or design from the beginning, landing perches and/or package capture and retrieval (via small dumbwaiter-like elevators) in place of wood/gas-burning fireplaces. Impact mitigation steps might also include flyovers over the landing areas with some sort of visual/audible warning given that the aerobot intends to land on the next pass.

Finally, an integrated approach to intelligent devices/appliances will be important to the usage of aerobots. For example, wireless intelligent device communication between CTOL/STOL aerobots with automobile operator for notification of impending merger into traffic during take off on landing on residential roadways. Alternatively, aerobot intelligent device wireless communication with residential housing doorbell devices or intercoms for automated delivery notifications and possible security certification. These are just two examples of the possible aerobot/intelligent device routine interactions required.

This coupling of aerial vehicles with other intelligent systems so as to enable wholly new types of mission applications has been discussed previously for both planetary science[22] and marine domain awareness[28] applications. Such integration/fusion of disparate systems – bound together by the dictates of autonomous system technology and robotics -- is an important emerging area of research investigation.

Table 7. Total System Elements/Requirements

Mission & Vehicle Type	**Robotic and/or telepresence systems to perform mobility or manipulation surface or interpersonal interactive" tasks post-flight**	**"Recycling" strategy for auxiliary delivery systems (e.g. how to get parachutes & deployment pods back to service providers)**	**Automated base camp (e.g. automated ground-handling, refueling and recharging, maintenance, and launch/recovery)**	**Central (human or machine-to-machine) control and coordination systems (service provider and/or customer/owner)**	**Fail-safe (aerial vehicle) flight termination decelerators & impact cushioning devices**	**Automated package air-deployment system (including steerable parachutes)**	**Pre-delivery automated notification and other authorization or concurrence systems or protocols**	**Customer/addressee delivery recovery systems (e.g. air-deployed package recovery nets, shelters or covered walkways for package ground drop-off post-landing)**
Home Delivery CTOL Platform	0	9	8	6	8	9	9	8
Home Delivery VTOL Platform	0	2	8	6	2	6	9	5
Courier-bot turbojet multi-fuselage CTOL	0	9	4	6	8	9	9	9
Pizza Delivery Flyer	0	0	9	6	8	6	2	6
Police-Bot	0	0	4	8	8	0	0	0
Security-Bot	6	0	8	8	8	0	0	2
Emergency-Bot	8	0	4	8	8	4	2	0
Anti-Bot	6	0	9	8	2	0	0	2
Camera-Bots	0	0	0	0	2	0	0	0
Eco-Bots	9	0	4	8	2	2	0	0

Note that each of the above system elements is qualitatively, but numerically, rated from 0-10 (from not important to very important to essential). Not included in the above table are the obvious and essential system requirements for advanced guidance, navigation and control systems (including but not limited to high-precision GPS navigation and vision- and other sensor-based situational awareness and collision-avoidance system elements, as well as intelligent health monitoring, prognostics and fault-tolerant adaptive vehicle sub-systems.

Conceptualization & "Plausible Design" Methodology

Having concluded the above discussion, it is now proposed that the aerobot and inter-space mission, or rather application, domain should now be examined, as a particularly noteworthy example, in the context of deriving and implementing new approaches or methodologies related to engineering design conceptualization and system analysis for technology portfolio identification and management. This work, though, is of potentially broader engineering research and development application.

Figure 24 is a high-level flow chart of the proposed conceptualization and technology portfolio system analysis process outlined in this paper. This work complements other related system analysis work for CTOL and vertical lift aircraft in the literature[16,29-32]. The key benefits of this proposed analysis methodology is a consistent approach to translate/map "societal/public good" goals to technology goals/objectives (heavily integrated with the conceptualization/conceptual design process) and thus on to defining specific technology portfolios, which can then be rigorously tracked throughout the design and development phases. Throughout this discussion a technology-driven (as compared to a market-driven approach) perspective is fostered. The work complements the "system analysis as applied to autonomy" work outlined in [16]. Throughout the following discussion, though, the aerobot/inter-space "application domain" will be used as a test case illustrating the utility of these design and system analysis concepts.

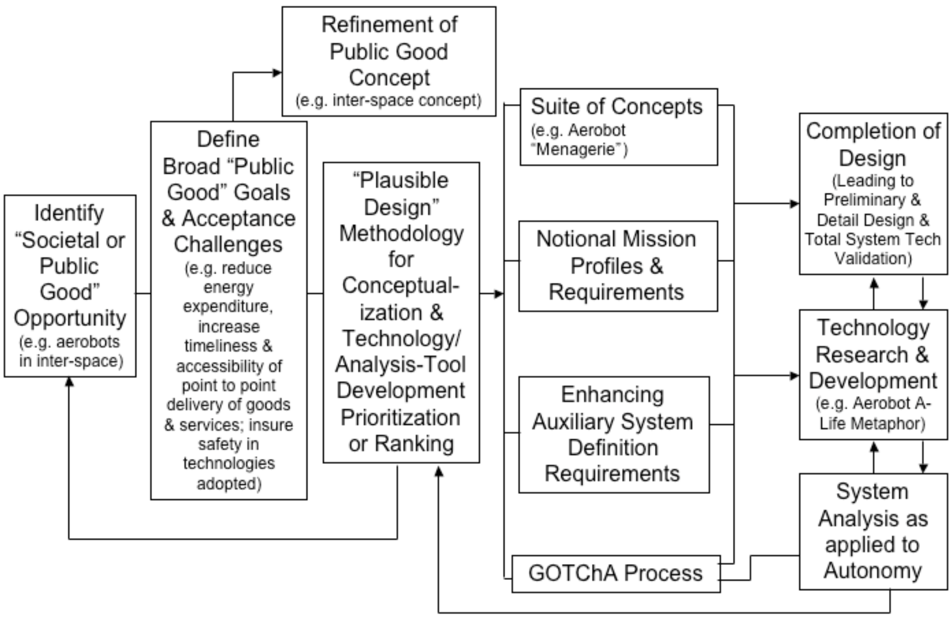

Fig 24. Aerobot Conceptualization-to-Development Process

The following discussion will focus more on the process of engineering "conceptualization" rather than design per se. The proposed conceptualization process begins with Figure 25, which illustrates several suggested "directions," or rather paradigm approaches, for innovative engineering conceptualization. (These are personal reflections upon future opportunities for aerial vehicle research and technology. Other, institutional and/or market-driven "technology directions" can be composed. For example, future technology direction guidelines for the automotive industry might emphasize ecological considerations, impact safety, and vehicle reliability and product longevity, to note just a few possibilities) Taking advantage of these "directions" are an aid to escaping evolutionary type designs that rely significantly on heritage tried and true concepts.

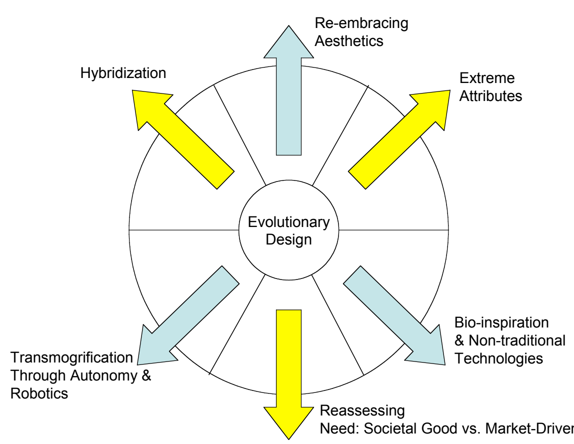

Fig. 25. Suggested Conceptualization "Directions" to Escape Evolutionary Design

The earlier described aerobot concepts/conceptual designs map to the recommended "conceptualization directions" (Fig. 25) as shown in Table 10. The richness and diversity of these initial plausible design aerobot concepts can be readily seen in that a reasonably uniform distribution/alignment with the conceptualization "directions" has been achieved (as represented by the Table 10 summary).

Table 10. Notional Vehicle Mapping to Conceptualization "Directions"

	Re-embracing Aesthetics	**Extreme Attributes**	**Bio-Inspiration & Non-Traditional Technologies**	**Reassessing Need**	**Autonomy & Robotics**	**Hybridization**
Home Delivery Hauler				Alternate approach to delivery of small packages		
Courier-Bots	In a vehicle class dominated by propulsion using propellers & IC-engines, the use of turbojets provide for sleek clean lines	"Trimaran" multi-fuselage configuration		Enhanced security through aerial versus ground transport of high-value items		
Pizza Delivery Flyer	Combination blended-wing-body and tilt wing STOL configuration	Accommodating (relatively) large atypically shaped (volume & mass) payload while being STOL capable		Alternate to private automobile delivery		
Police-Bot	Exotic multi-rotor (three) configuration; updating an old concept					
Security-Bot				Mobile versus immobile, proactive versus reactive, surveillance and security devices		
Emergency-Bot	Re-examining conventional tiltrotor geometry; updating an old concept			Dealing with urban congestion; networking to address limited resources; augmenting ground support	Carrier platform for a ground-deployable tele-operated and/or automated emergency "kit"	
Anti-Bot	Insect-like appearance, motions, & behaviors; one-bladed rotors		"Hunt" and/or divert away other aerobots or intruders			Fusion of flapping and rotary-wing propulsion
Camera-Bots				Taking consumer imaging to a completely new level		Camera chassis as the primary element of vehicle fuselage
Eco-Bots	"Organic" appearance; embodiment of "Mech Life"		Autonomous mechanisms for environmental or biological sampling	Replace human field agents taking samples	Robotic arms/manipulators for sampling	Hybrid mobility for (ground and air)

Note that if Table 10 were sparsely populated or narrowly focused on one or two conceptualization "directions," then the earlier defined suite of conceptual designs should be found lacking and needs to be revisited.

An alternate approach to current conceptual design practices is now suggested which emphasizes an (iterative) balance between concept and technology development. This "plausible design" methodology is subsequently shown to have significant implications for the integration of conceptualization, conceptual design, system analysis, and technology portfolio identification and management.

Critique of Current Conceptual Design Practices:

1. *Conceptual design practice has been heavily weighted to incorporate higher levels of fidelity of analysis earlier and earlier in the conceptual process and market-identification stages. On the face of it, this has been a commendable trend. However, the pendulum has swung too far and the aesthetic—and disruptive -- aspects of design have been diminished to near insignificance.*
2. *We tend to design to what our analytical tools and design heritage and engineering experience allows; i.e. if new analysis or theoretical work is required to fully design/mature a concept, then that concept tends not to proceed beyond the initial concept screening; this results in incremental, or rather evolutionary, progress in system design rather than allowing for revolutionary design concepts and application domains.*
3. *Further there oftentimes results an institutional – even sometimes an industry-wide – inertia, that can over the course of years or even decades, unnecessarily restrain the adoption of new design concepts, technologies, and application opportunities.*

A new methodology will now be introduced for evaluating sets of early to mid-stage competing conceptual designs, representing diverse solution approaches to mission requirements, while at the same time accounting for uncertainty in the design analysis/technologies employed. Further, the focus of the analysis will be on the conceptualization and conceptual design evaluation of "systems" (which includes multiple heterogeneous platforms, mission equipment payloads, and other auxiliary systems, etc) rather than "vehicles." Figure 26 is a simple illustration of the iterative nature of the overall proposed process.

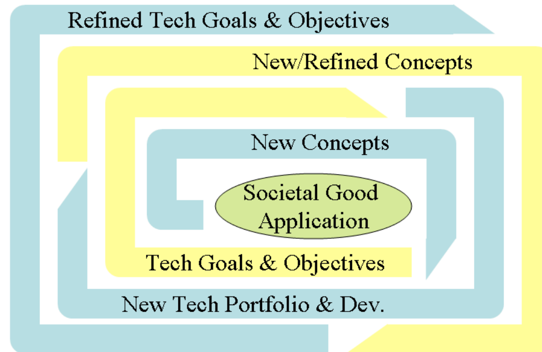

Fig. 26. New Concepts lead to New Technologies lead to New Concepts…All Stemming from Societal Good Goals

This plausible design methodology is particularly suited to assessing disparate vehicle types (with and without enabling auxiliary systems such as payload deployment via parachute or tether for the small package delivery application) in the earliest stages of conceptual design.

Plausible Design Principles & Propositions:

1. *A strong linkage should be shown, and effectively managed from an engineering management perspective, between "societal/public good" needs/requirements and the technologies being developed.*
2. *A key outgrowth of the design process should be the identification, development, and validation of new technologies – i.e. the creation of a technology portfolio.*
3. *The key to defining and managing a robust technology portfolio is to link that process with a prolific and diverse suite of conceptual design concepts.*
4. *More is better when it comes to ideas, even if less than ideal analysis tools/techniques need be used (as long as appropriate cautionary steps and methodologies are employed to account for varying levels of modeling/predictive fidelity).*
5. *The size and robustness of a suite of plausible conceptual designs is directly proportional to the viability/sustainability of the notional application domain to which the concepts are intended to address. I.e., if many good concepts are generated for a given application then the more likely this application is a valid one to invest in. A paucity of concepts (or even worse,*

a singular solution suggested early in the design phase) begs the question of the viability of the particular application niche identified.

The end products of the plausible design process are not the vehicle conceptual/preliminary designs themselves, but the scoping of the requirements and design space, identifying critical technology goals and objectives and making technology portfolio decisions. Figure 27 summarizes the plausible design methodology flow chart.

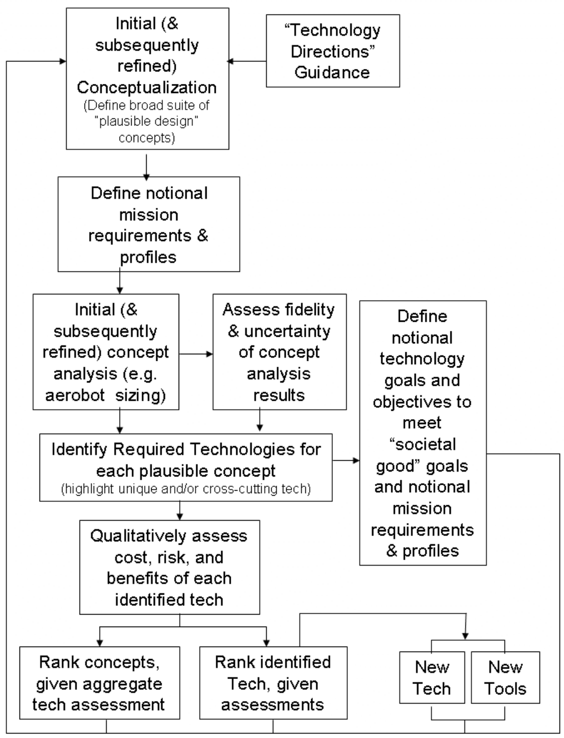

Fig. 27. Plausible Design Process.

With reference to Fig. 27, the proposed plausible design methodology discussion will now be rounded out with the summarizing of some important concepts, essential analytical relationships for design/technology assessment, and other important methodological considerations.

The first step to the plausible design process is to define a broad societal or public good goal to define an application domain to address. Next, a suite of notional conceptual designs is proposed and initial feasibility assessed via a variety of variable fidelity design tools. Various levels of design tool fidelity are defined in Table 11. This level of fidelity table for analysis/design-tools is analogous in many ways to the NASA/DOD Technology Readiness Level (TRL) "barometer" for benchmarking the maturation of various technologies proposed for an engineering system. There are two components of the level of fidelity scale: scope of analysis and accuracy. (The scope of the analysis refers to the number of disciplines and notional conditions studied – both on- and off-design point.)

Table 11. Analysis/Assessment Fidelity Levels

Fidelity Level	Description
10	"Exact" analytical solution predictive capability for the general class of (total) system design (including key support systems) and application being studied/designed
9	Highly accurate (less than 1% uncertainty for appropriate performance metrics) physics-based, validated predictive capability all aspects, i.e. all technical disciplines, all sub-systems (both as isolated components and integrated system) applicable to the (total system) design problem; (total) system design (including key support systems) validated with comprehensive test data.
8	Complete integrated system analysis (with very limited support system analysis); complete operating matrix examined, including off-design-points; less than 1% uncertainty in all analyses performed; all key sub-systems have expansive data sets with some limited integrated/complete system testing/validation
7	Complete/integrated system analysis (excluding support systems) for all key design points; limited off-design-point conditions examined as a total ; less than 5% uncertainty in all analyses performed; limited sub-system/component validation testing
6	Analysis limited only to the most critical technical disciplines/sub-systems for the design; off-design point operating conditions examined; 1-5% uncertainty for key parameters at key operating conditions analyzed
5	5-10% uncertainty for key parameters analyzed; analysis limited only to the most critical technical disciplines/sub-systems for the design ; limited operating conditions examined, principally the most critical or demanding design point(s)
4	10-25% uncertainty for key parameters analyzed; analysis limited only to the most critical technical disciplines/sub-systems for the design ; limited operating conditions examined, principally the most critical or demanding design point(s)
3	Simplified (one to two key performance metrics for the most crucial operating condition(s)) model- and/or simulation-based analysis. Greater than 25% predictive uncertainty for the predicted key parameters/conditions.
2	Key hardware design/definition and feasibility "assessment" based on allusion to heritage system and subsystem design/operational experience.
1	Broad design characteristics defined and "feasibility" established via intuition and/or engineering judgment.
0	"Eureka" moment; sketchiest inclinations of a good idea.

Having derived (with very low fidelity, level 0-3 in Table 11) a suite of notional conceptual designs, the challenge then is to approximately map or generalize required system performance metrics for this suite of concepts to technical goals and objectives compatible with the well-known GOTChA (Goals, Objectives, Technical Challenges, and Approaches) process[43]. By and large, though, GOTChA goals and objectives are defined by subject matter expert semi-qualitative input. A potentially more rigorous approach is now proposed.

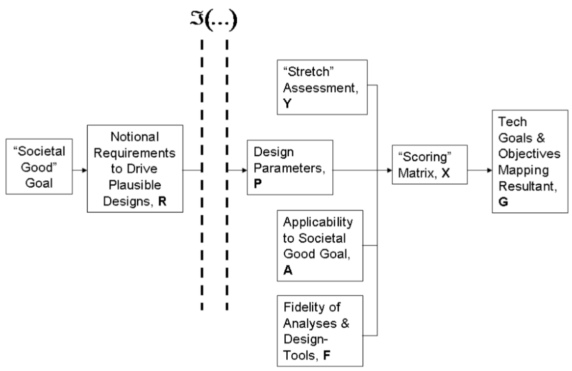

Fig. 28. Mapping System Performance Metrics (for a suite of system conceptual designs) to GOTChA-type Technical Goals and Objectives

The equivalent analytic relationships to Fig. 28 mapping are given by Eqs. 12-23. As expressed in Eq. 12, the total system design parameters matrix, **P**, is the result of some generalized operator, $\Im(\ldots)$, as applied to the mission requirements, **R**. Conceptually, this nonlinear (and perhaps iterative) operator embodies the sum total of analyses and design-tools as applied to the design problem, at a given assumed level of fidelity; knowing the form and functionality of the $\Im(\ldots)$ operator is not required for the purposes of this paper. Refer to [26], for example, for alternate expressions for "design equations."

$$\mathbf{P} = \Im(\mathbf{R}) \qquad (12)$$

In general, the functional requirements matrix has the form

$$\mathbf{R} = \begin{bmatrix} & \textit{Req, \# 1} & \cdots & \textit{Req. \# N} \\ \textit{Concept \# 1} & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ \textit{Concept \#M} & \ldots & \ldots & \ldots \end{bmatrix} \qquad (13)$$

Where for aerobots, the requirements matrix might look like

$$\mathbf{R} \to \begin{bmatrix} & \textit{Range (km)} & \textit{Payload (kg)} & \cdots \\ \textit{Concept \# 1} & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ \textit{Concept \#M} & \ldots & \ldots & \ldots \end{bmatrix} \qquad (14)$$

As will be seen later, Table 3 satisfies the specific functional requirements – thus populating the general functional requirements matrix of Eq. 13 -- for the notional aerobots noted in this paper.

The general form of the design parameters matrix is as follows

$$\mathbf{P} = \begin{bmatrix} & \textit{Param. \# 1} & \cdots & \textit{Param. \# O} \\ \textit{Concept \# 1} & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ \textit{Concept \# M} & \ldots & \ldots & \ldots \end{bmatrix} \qquad (15)$$

Where, again, the operator, $\Im(\ldots)$, maps the functional requirements to the design parameters, with some given level of fidelity (dependent in part on what phase of the design/analysis process is being undertaken) for each parameter estimate. It should be noted that the design parameter matrix can be partitioned into three (semi-dependent) sub-matrices: system-level, $\mathbf{P}_1$ and constituent-level performance parameters, $\mathbf{P}_2$, and operating or environmental parameters, $\mathbf{P}_3$. Let the size of the $\mathbf{P}_1$ matrix be MxO_1, the size of $\mathbf{P}_2$ sub-matrix be MxO_2, and the size of the $\mathbf{P}_3$ sub-matrix be MxO_3. This design parameter partitioning gains its greatest efficacy when used to help define GOTChA-type goals and objectives, as seen later. In that context, the design parameters should be adjusted to reflect the maximizing – not minimizing -- their values is desirable from a design perspective.

$$\mathbf{P} = [\mathbf{P}_1 \mid \mathbf{P}_2 \mid \mathbf{P}_3] \qquad (16)$$

Specifically, for the aerobot application the design parameter (and associated partitioning) matrix looks like as follows, using familiar aircraft design system- and constituent level design/performance parameters. Note that in the example constituent design parameter matrix, $\mathbf{P}_2$, that the inverse of the profile drag coefficient is used, instead of the coefficient itself, as conventionally done, so as to adhere to the "maximizing the design parameters is good" precept employed in this analysis. (Note that the inverse of the earlier derived mission energy expenditure metric, E, and the impact/collision distributed energy, ζ, could be introduced into the design parameter matrix for the aerobot application domain.)

$$\mathbf{P}_1 \rightarrow \begin{bmatrix} L/D\big|_{\max_1} & T/W\big|_{\max_1} & \cdots \\ \cdots & \cdots & \cdots \\ L/D\big|_{\max_M} & T/W\big|_{\max_M} & \cdots \end{bmatrix}$$

$$\mathbf{P}_2 \rightarrow \begin{bmatrix} C_{Lmax1} & 1/C_{do1} & \cdots \\ \cdots & \cdots & \cdots \\ C_{LmaxM} & 1/C_{doM} & \cdots \end{bmatrix}$$

$$\mathbf{P}_3 \rightarrow \begin{bmatrix} Mach_1 & \mathrm{Re}_1 & \cdots \\ \cdots & \cdots & \cdots \\ Mach_M & \mathrm{Re}_M & \cdots \end{bmatrix}$$

(17a-c)

Next, a "stretch" matrix, **Y** is defined so as to be associated with the design parameter matrix, **P**, such that their element numeric values are defined by technical discipline subject matter experts to indicate the degree of difficulty in technological achieving individual design parameter (system- and constituent-level) performance levels.

$$\mathbf{Y} = \begin{bmatrix} & \begin{matrix} Tech\ \text{"}Stretch\text{"} \\ to\ Achieve\ Param.\ \#\ 1 \\ For\ Given\ Concept \end{matrix} & \cdots & \begin{matrix} Tech\ \text{"}Stretch\text{"} \\ to\ Achieve\ Param.\ \#\ O \\ For\ Given\ Concept \end{matrix} \\ Concept\ \#\ 1 & (0\ low\ to\ 10\ high) & \cdots & (0\ low\ to\ 10\ high) \\ \cdots & \cdots & \cdots & \cdots \\ Concept\ \#\ M & \cdots & \cdots & \cdots \end{bmatrix}$$

(18)

And further, the following "value" vector, **A**, and "fidelity" matrix, **F**, can be defined

$$\mathbf{A} = \begin{bmatrix} Applicability\ of\ Concept\ \#\ 1\ to \\ \text{"}Societal\ Good\text{"}\ Goal\ (0\ low\ to\ 10\ high) \\ \cdots \\ \cdots \\ \cdots \\ Applicability\ of\ Concept\ \#\ M\ to \\ \text{"}Societal\ Good\text{"}\ Goal\ (0\ low\ to\ 10\ high) \end{bmatrix} \quad (19)$$

$$\mathbf{F} = \begin{bmatrix} & \begin{matrix} Fidelity\ to\ Predict \\ Param.\ \#\ 1\ For\ Given \\ Concept \end{matrix} & \cdots & \begin{matrix} Fidelity\ to\ Predict \\ Param.\ \#\ O\ For\ Given \\ Concept \end{matrix} \\ Concept\ \#\ 1 & (0\ low\ to\ 10\ high) & \cdots & (0\ low\ to\ 10\ high) \\ \cdots & \cdots & \cdots & \cdots \\ Concept\ \#\ M & \cdots & \cdots & \cdots \end{bmatrix}$$

(20)

The definition of these various different matrices culminates with the definition of a final "scoring" matrix, which can be derived using the following relationship

$$\mathbf{X}_{i,j} = f\left(\mathbf{F}_{i,j}\right)\mathbf{A}_i\mathbf{Y}_{i,j}\mathbf{P}_{i,j} \quad (21)$$

Where a nonlinear function dependent upon the level of fidelity used to establish a given design parameter could be given as

$$f\left(\mathbf{F}_{i,j}\right) \rightarrow a\mathbf{F}_{i,j}e^{-b\mathbf{F}_{i,j}} \quad (22)$$

Further, where the prescribed constants a≈5 and b≈0.2 are suggested. Note this implies that there is an optimum analysis/design-tool level fidelity where maximum scoring is given to the design parameters as to establish technology goals and objectives. In other words, if the modeling/predictive capability is too accurate/mature (as represented by the level of fidelity assessments) then the resulting technical goals/objectives are probably too conservative and, therefore, too readily achievable.

Values assignments for associated, or complementary, system- and constituent-level design parameters (members of $\mathbf{P}_1$ and $\mathbf{P}_2$) should be consistent with respect to each other. I.e., a system-level design parameter should not be assigned values (for **Y**, **F**, and **X**) that are significantly higher or lower than constituent design parameters that are associated with or complement (in other words, directly influence) the system-level design parameter. The converse should also be true. In only this regard can a proper relational ranking of goals (system) metrics with objectives (constituent) metrics be preserved.

Finally possible technology goals and objectives follow notionally from the following sorting/ranking process (Eq. 23a-b), based upon the above noted scoring matrix, **X** (Eq. 21).

$$
\mathbf{G}_1 = \left[\begin{array}{cc|ccc}
 & \overbrace{\textit{Goal for Given System-Level Parameter}} & & \overbrace{\textit{Conditions at Which Goals Must be Met}} & \\
\textit{Param. \# 1} & \begin{array}{l} \textit{Assigned value of } \geq \mathbf{P}_{a,1} \textit{ (or } \mathbf{P}_{1_{a,1}} \textit{)} \\ \textit{where } a \textit{ is the indice where} \\ \mathbf{X}_{a,1} = \max\left(\mathbf{X}_{1,1},\ldots,\mathbf{X}_{M,1}\right) \end{array} & \mathbf{P}_{3_{a,1}} & \ldots & \mathbf{P}_{3_{a,O_3}} \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
\textit{Param. \# } O_1 & \begin{array}{l} \textit{Assigned value of } \geq \mathbf{P}_{b,O_1} \textit{ (or } P_{1_{b,O_1}} \textit{)} \\ \textit{where } b \textit{ is the indice where} \\ \mathbf{X}_{b,O_1} = \max\left(\mathbf{X}_{1,O_1},\ldots,\mathbf{X}_{M,O_1}\right) \end{array} & \mathbf{P}_{3_{b,1}} & & \mathbf{P}_{3_{b,O_3}}
\end{array} \right]
\tag{23a}
$$

$$
\mathbf{G}_2 = \left[\begin{array}{cc|ccc}
 & \overbrace{\begin{array}{c}\textit{Constituent-Level Parameters} \\ \textit{(Candidates for Tech Objectives)}\end{array}} & & \overbrace{\textit{Conditions at Which Objectives Must be Met}} & \\
\textit{Param. \# } O_1+1 & \begin{array}{l} \textit{Assigned value of } \geq \mathbf{P}_{\alpha,O_1+1} \textit{ (or } \mathbf{P}_{2_{\alpha,1}} \textit{)} \\ \textit{where } \alpha \textit{ is the indice where} \\ \mathbf{X}_{\alpha,O_1+1} = \max\left(\mathbf{X}_{1,O_1+1},\ldots,\mathbf{X}_{M,O_1+1}\right) \end{array} & \mathbf{P}_{3_{\alpha,1}} & \ldots & \mathbf{P}_{3_{\alpha,O_3}} \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
\textit{Param. \# } O_1+O_2 & \begin{array}{l} \textit{Assigned value of } \geq \mathbf{P}_{\beta,O_1+O_2} \textit{ (or } P_{2_{\beta,O_2}} \textit{)} \\ \textit{where } \beta \textit{ is the indice where} \\ \mathbf{X}_{\beta,O_1+O_2} = \max\left(\mathbf{X}_{1,O_1+O_2},\ldots,\mathbf{X}_{M,O_1+O_2}\right) \end{array} & \mathbf{P}_{3_{\beta,1}} & & \mathbf{P}_{3_{\beta,O_3}}
\end{array} \right]
\tag{23b}
$$

The ranking/sorting of system- and constituent-level design parameters implicit in Eq. 23a-b allows for subsequent efforts by a system analyst to craft GOTChA charts and other similar project/program planning tools. It should be emphasized that Eq. 23a-b, and the associated above outlined analysis, is merely an aid to helping establish technology goals and objectives and not some rigid stricture to follow.

It is now proposed that work in [16], that was applied to assessing the technology portfolio for autonomous system technologies, can analogously be extended to general technology portfolio decisions -- as early as the conceptualization and conceptual design process – for any suite of (non-autonomous system) technologies applied to a broad class of system design problems. (Note, it is still recommended that when assessing the technology portfolio for autonomous system technologies that the original methodology of [16] is still ascribed to.)

Before undertaking the question of how to rank technologies applied to a particular "societal good" goal, it is important to ask a few questions. First, is the technology portfolio assessment intended to make individual system concepts more feasible? Or, alternatively, is it intended to make the aggregate suite of system concepts more feasible? An even more general objective might be to make the tech goals, rather than the concepts, more feasible. Or, ultimately, is it not the intent of such technology assessments to increase the likelihood of achieving the “societal good” goal? As a minimum, the last two most general and important questions are the ones that must and will be addressed in this paper.

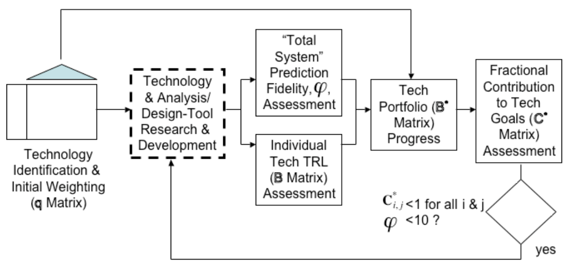

Fig. 29. Assessing Technology Portfolios based on Plausible Design Established Technology Goals & Objectives

The proposed technology portfolio analysis takes the technology goals and objectives, derived (in part) from the plausible design methodology, culminating in Eq. 23, and uses that information to populate a Quality Function Deployment[27] (QFD) inspired “house of quality” tabular matrix, of the general form of Fig. 30. (Detailed and specific forms of this QFD tabular matrix for aerobots – both for non-autonomous and autonomous system technologies – will be shown later in the paper.) The development of this QFD-inspired “**q** matrix” (or, alternatively, the predecessor [16] **Q** matrix for comparable portfolio assessments applied to autonomous system technologies) is the province of the subject matter (technical discipline) experts supporting the conceptual design team.

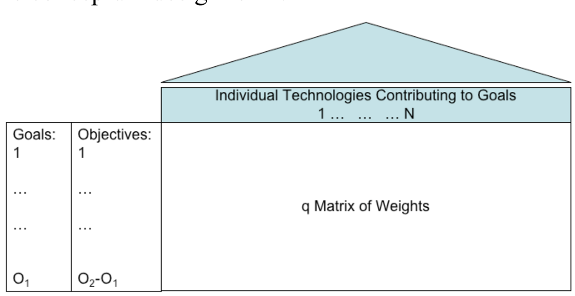

Fig. 30. General Format of QFD-Inspired Tabular Matrix

The **q** matrix weights, $\mathbf{q}_{i,j}$, in Fig. 30 can be determined as per Eq. 24. This initial weighting factor scheme assumes that contributing individual technologies all uniformly/equally contribute to the i'th Goal with a nominal partitioning between enabling (A=0.0143 or 1/70) and contributing technologies (A=0.0036 or 1/4·1/70). The parameter N_{CTjTiG} is the number of contributing technologies, including j’th technology, to i’th goal. (The weighting $\mathbf{q}_{i,j} = A/N_{CTjTiG}$ is consistent with the work of [16].) Four new parameters (array/vectors) have been added to **q** matrix weighting considerations. The **T** array represents the core competency expertise or growth interest (and therefore anticipated institutional benefit) in a particular individual technology, ranging from 0 no expertise/interest to 10 high expertise/interest. The **D** array represents the consistency of the particular individual technology with the technical direction guidance given (for example, refer to Fig. 25), ranging from 0 for no adherence to technical guidance to some maximum positive integer representing the number of technical direction guidelines given. (For example, a technology embodying attributes of all of Fig. 25 conceptualization directions, or guidelines, would have a **D** array element value of “6.” Incorporating only attributes for two technical direction guidelines would yield a **D** array element value of “2” and so on.) The **U** array represents the risk of development/implementation of a particular individual technology (1 low to 10 high). And, finally, the **K** array represents the cost associated with the development/implementation of a particular individual technology (1 low to 10 high). In this manner the weighting factors can reflect resource/funding issues that may not fully stem from engineering considerations alone (i.e. not all promising technologies may be funded at the required levels, or funded at all, to achieve the anticipated contributions to the technology goals).

$$\mathbf{q}_{i,j} = \frac{A}{N_{CTjTiG}} \cdot \frac{\mathbf{T}_j\left(1+\mathbf{D}_j\right)}{\left(\mathbf{U}_j \mathbf{K}_j\right)} \tag{24}$$

Subsequent iterations on the $\mathbf{q}_{i,j}$ weighting factors can be adjusted to reflect detailed analysis results and/or simulations that show the proportional influence of individual technologies to the goals.

The earlier system analysis work of [16] focused on tracking the progress of individual autonomous system technologies against primarily a metric that measured ideally increasing aerial vehicle “intelligence.” In this work, the intelligence metric will be analogously swapped out of the basic derived technology portfolio analysis methodology and substituted with a “total system” predictive capability "level of fidelity" metric, φ; φ can be established independently through engineering judgment or can be based on the earlier defined design parameter fidelity matrix, **F**, and stretch matrix, **Y**, refer to Eq. 25 (rounded off to the nearest integer). In both cases, increasing intelligence and overall predictive capability fidelity are inherently seen as desirable from a research and technology perspective.

$$\varphi \approx \sum_i \sum_j \mathbf{F}_{i,j} \mathbf{Y}_{i,j} \Big/ \sum_i \sum_j \mathbf{Y}_{i,j} \qquad (25)$$

Relating the development progress and contribution of individual technologies, represented by the j[th] array element $\mathbf{B}_j^*$, to technology maturity and overall system predictive level of fidelity is performed (in part) by the expression

$$\mathbf{B}_j^* = \frac{\mathbf{W}_j^* \mathbf{B}_j + (\varphi/10) W_0^* \mathbf{I}_j^*}{\mathbf{W}_j^* + W_0^*} \qquad \text{for } j \geq 1$$

(26)

Where φ is the ($0 \leq \varphi \leq 10$) "total system" predictive (including validation) capability "level of fidelity" (versus the individual parameter/technology fidelity discussed earlier in the plausible design definition of the fidelity matrix, **F**) for the suite of technologies and application domain studied. (Refer again to Table 11.)

Equation 26 clearly reinforces the idea that total system level of fidelity, φ, is the key driver underlying defining/tracking new concepts and technologies in this proposed methodology (see Fig. 31). Increasing modeling/predictive level of fidelity helps describe an expanding "wave front" as to the boundary of the plausible and implausible as to engineering designs and new missions/applications. In this regards, the metric φ, level of fidelity, for new design concepts/technologies is very much analogous to the metric ι^*, normalized *intelligence*, for defining/tracking (the specialized case of) emerging autonomous system technologies [16].

Note that W_0^* and $\mathbf{W}_j^*$ comprise a set of relative weights given to the two types of technology assessments embodied in Eq. 26. The weight W_0^* is given to a "total system" prediction capability assessment. The weight $\mathbf{W}_j^*$ is given to an assessment of the individual technology's normalized technology readiness level (TRL), or as otherwise denoted by

$$B \equiv \begin{bmatrix} \textit{TRL of the 1st Technology divided by "9"} \\ \ldots \\ \textit{TRL of the jth Technology divided by "9"} \\ \ldots \end{bmatrix}$$

(27)

Assessments of φ and **B** are generally qualitative and provided by (technical discipline) subject matter experts (though in the case of φ validation of predictive capability is required for the higher levels of φ). Note by definition that $W_0^* + \mathbf{W}_j^* = 2$ must hold true for all technologies, i.e. all values of j. The weights $\mathbf{W}_j^*$ are specified as follows, relying on the matrix **q**, which in turn is derived from the QFD-inspired tabular matrix shown in Fig. 30.

$$\mathbf{W}_j^* = a\mathbf{I}_j^* \quad \text{and} \quad \mathbf{I}_j^* = u\left(10\frac{\mathbf{W}_j}{W_F} + \varphi - 9\right) \qquad (28a\text{-}b)$$

Where

$$W_F = \max(\mathbf{W}) \quad \text{and} \quad \mathbf{W}_j = \sum_i \mathbf{q}_{i,j} \qquad (28c\text{-}d)$$

The constant "a," Eq. 28a, is arbitrarily assigned to reflect the relative weight of $\mathbf{W}_j^*$ with respect to $\mathbf{W}_0^*$; a=1.0 is suggested. The array **W** can be thought of as denoting the relative importance of each individual technology, based upon the **q** matrix input, as to contributing the overall goals of the project.

Finally, the progress towards developing individual technologies needs to be tracked against progress towards overall programmatic technology goals/objectives. This is accomplished in the proposed analysis by the following relationship for "fractional anticipated contribution to goal" array, $\mathbf{C}_i^*$.

$$\mathbf{C}_i^* = \mathbf{C}_i \Big/ \sum_j \mathbf{q}_{i,j}$$

(29)

Where

$$\mathbf{C} = \mathbf{q}\mathbf{B}^*$$

(30)

Note that by definition, for a given i'th row of the matrix **q**, the following holds true

$$\sum_j \mathbf{q}_{i,j} \leq 1 \qquad (31)$$

The end-product of the above plausible design methodology -- with its emphasis on robust conceptualization, a Concepts-to-Tech-Goals strategic perspective, and the necessity for rigorous technology portfolio management -- is intended as an unified process by which increased physical understanding, as represented by increasing modeling/predictive level of fidelity, is recognized as the key driver for pushing outward the boundary of the plausible/implausible as to new concepts, new technologies, and enhanced societal good (Fig. 31).

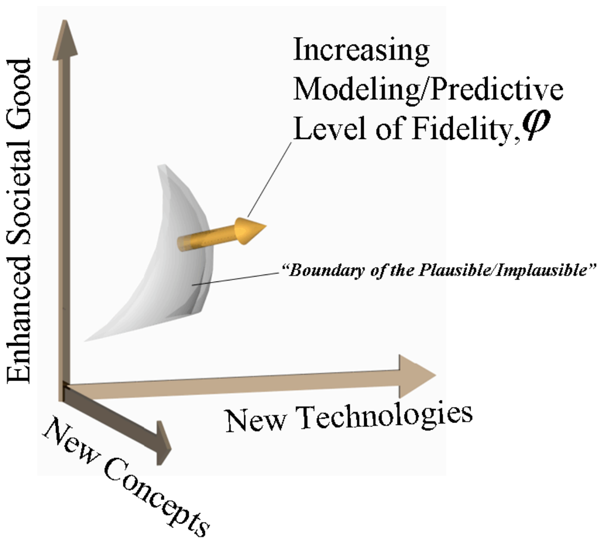

Fig. 31. "Total System" Level of Fidelity and the Boundary of the Plausible/Implausible

Concluding Remarks

This paper has had two primary objectives: (1) to advance a new vision (aerobots operating in inter-space) for future vertical lift aircraft design and (2) new conceptualization and system analysis tools are proposed and discussed in the context of defining technology goals and objectives as well evaluating the technology portfolio necessary to meeting those goals and objectives.

With regards to the first objective, an alternate vision of future possibility for vertical lift aircraft is advanced. The vision of this new world: a kind of cross between the Jetson sky-cars and swarms of mechanized insects. Seeing aerobots flying over the San Francisco Bay Area, going down Hwy 101 toward the Hwy 101/880 junction and pealing off in either direction, then seeing the aerobots going past the airport on Hwy 17 south, and peeling off through a corridor to the airport or a distributor/retailer shipping depot -- all this to provide the capability for distributing small, time-sensitive, high-value goods and services to the public, all the while potentially saving energy, enhancing quality of life, and even, perhaps, saving lives or preserving health. The aerobot revolution is in its infancy. Let us be proactive and help shape this revolution to maximize the beneficial role that aerial robots can play in our lives. Therefore, the vision of "inter-space" -- a "final frontier" for aviation – is advanced for consideration.

Secondly, new analysis tools have been outlined that revealed new design parameters/relationships, as well as engendered new approaches to defining/assessing technology goals and objectives and the technology portfolio necessary to accomplish those goals and objectives. Using the aerobot/inter-space concept as an illustrative test case, key attributes of these analysis tools were discussed. In particular, new parameters/relationships were defined and discussed as to impact/collision mitigation (unequivocally a key concern for small aerial vehicles intentionally flying in close proximity to people and property) and its influence on aerobot design. Further, a "plausible design" methodology (including personal insights/comments on the nature of conceptualization "directions," or guidelines, for design) for engineering design and the identification of technology goals and objectives was outlined. This was followed by comments related to technology portfolio management, and by some comments on specific technologies/challenges for the aerobot/inter-space concept. Finally, some thoughts related to conceptual design of small aerial vehicles is presented as precursor information required for conducting technology portfolio assessments; as a consequence some notional sizing results, as well as some pertinent comments related to sizing methodologies applied to small vehicles and propulsion systems, are presented.

The above outlined work is a very modest step forward examining the future of vertical lift aircraft design. Considerably more work remains to examine some of the identified important issues related to aerobots, in particular, and vertical lift aircraft design and analysis, in general.

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