A Multi-Modality Mobility Concept for a Small Package Delivery UAV

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Abstract

This paper will discuss an alternate approach to the typical notional small package delivery drone concept. Most delivery drone concepts employ a point-to-point aerial delivery CONOPS from a warehouse directly to the front or back yards of a customer's residence or a commercial office space. Instead, the proposed approach is somewhat analogous to current postal deliveries: a small aerial vehicle flies from a warehouse to designated neighborhood VTOL landing spots where the aerial vehicle then converts to a "roadable" (ground-mobility) vehicle that transits on sidewalks and/or bicycle paths till it arrives at the residence/office drop-off points. This concept and its associated platform or vehicle will be referred in this paper as the MICHAEL (Multimodal Intra-City Hauling and Aerial-Effected Logistics) concept. It is suggested that the MICHAEL concept potentially results in a more community friendly "delivery drone" approach.

Nomenclature

b	(Primary) wing span, m
C	Circuituity, $C=(d_A - d_M)/d_M$, nondim.
c	(Primary) wing mean chord, m
C_D	Vehicle in-flight (cruise) drag coefficient, D/qS
C_L	Vehicle in-flight lift (cruise) coefficient, L/qS
C_P	Vehicle total rotor-shaft-output hover power coefficient
C_T	Vehicle hover rotor (aggregate) thrust coefficient
d_A	Actual distance traveled, miles or km
d_{AG}	Actual distance traveled on the ground (versus in the air), miles or km
d_M	Minimum point-to-point ("straight line") distance, miles or km
ESC	Electronic speed controllers
G	Ground travel ratio, $G=d_{AG}/d_A$
L/D	Vehicle in-flight (cruise) lift-over-drag ratio

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q	Freestream dynamic pressure, lb_f/ft^2 or N/m^2
S	Wing planform area, S=bc, ft^2 or m^2
α	Vehicle angle-of-attack, AOA, Deg.

Introduction

There is considerable socio-economic and public-service potential to small autonomous aerial vehicles, Refs. 1-4. In particular, the economic potential of small "delivery drones," e.g. Ref. 1, has captured considerable interest. But, despite the potential, there are many challenges to be overcome to see the realization of such mission applications. Among those challenges is that these vehicles and their associated CONOPS must be seen as being community friendly in terms of minimizing their noise, emissions, and invasiveness. If these challenges can be overcome, then society will benefit in terms of economic growth while minimizing environmental impact.

For any small package-carrying autonomous aerial vehicle concept to ultimately prove viable it must achieve one or more of the following goals: 1. reduce delivery time as compared to ground transportation alternates; 2. improve economics of package delivery service thorough reduced labor and increased customer satisfaction; 3. improve energy efficiency of delivery service; 4. reduce environmental emissions; 5. reduce roadway and tranportation system infrasture development pressure; 6. improve reliability and quality of potentially critical delivery services, particularly those impacting health-care services to seniors and underserved populations. Additionally, in general, any viable small package delivery drone must also meet the following design and operational constraints: 1. be as safe as or safer than the baseline delivery ground transportation system; 2. generate less than current community annoyance levels for emissions and noise from ground transportation and other community noise sources; 3. be seen as minimally invasive as to community/personal privacy; 4. must be all-weather reliable as to yield timely package deliveries; 5. be seen as providing secondary public services and community enhancements in addition to the primary mission of commercial small package deliveries.

It is still generally unproven whether some of the many delivery goods and services distribution concepts being proposed over the past few years can successfully meet the above noted goals and design and operational constraints. This paper seeks to closely consider some of these issues and propose an alternate goods and services aerial vehicle distribution system. Accordingly, a novel approach to the delivery drone paradigm is proposed. Throughout this paper this approach will be referred to as the MICHAEL (Multimodal Intra-City Hauling and Aerial-Effected Logistics) concept and its associated platform or vehicle.

General Problem Area:

How to improve the community friendliness of uninhabited aerial vehicles (UAVs) performing on-demand small package delivery or courier services?

1. Are there alternative concepts of operation (CONOPs) of delivery drones that could satisfy the potential market for fast, on-demand, delivery of small packages/cargo without requiring their close flyover (<30m or <100 feet AGL) over residences and takeoff and landing onto personal property?
2. Are there safe and efficient VTOL aerial vehicle configurations that could support – in fact be ideally uniquely tailored to – such a CONOPs?

Proposed Solution:

The MICHAEL concept will focus on the examination of a small "roadable" (or, more correctly, a sidewalk or bike lane compatible ground mobility) hybrid aerial vehicle that can not only vertically takeoff and land but also ideally cruise with airplane-like efficiency.

Instead of landing in someone's yard to deliver a package, the vehicle would land at a neighborhood landing site and then have the vehicle move with wheeled locomotion, on sidewalks and bike lanes, to the individual residences. This alternate approach to delivery drones might be seen as more community friendly than concepts of operation that require (very close) proximity to residences, personal property, and people/animals.

The solution space to be explored, then, is the use "roadable aircraft" in the context of small VTOL UAVs – versus past studies in the literature examining larger passenger-carrying aerial vehicles – to make such vehicles multimodal (air and ground) mobility platforms to act as community robotic "postal carriers" for intra-city deliveries.

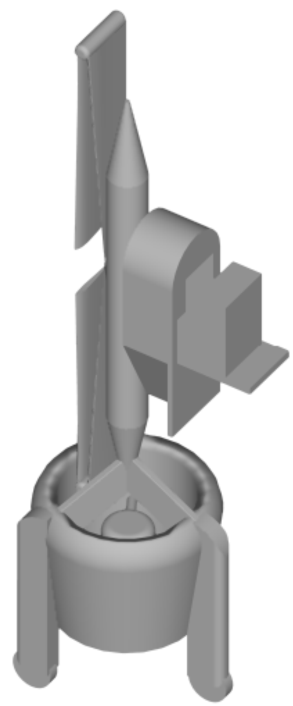


Fig. 1 – Package Delivery Using a MICHAEL System (package being shown extracted from payload fairing)

Mission Requirements

Figure 2 shows a notional mission profile for a MICHAEL platform. This mission profile is roughly consistent with other delivery drone CONOPS being proposed for the in-flight portion of the MICHAEL mission. It is also consistent with early work by the author in Ref. 1. However, midway through the mission – instead of landing or hovering over a residence or commercial delivery point – instead the vehicle lands at a designated neighborhood landing spot.

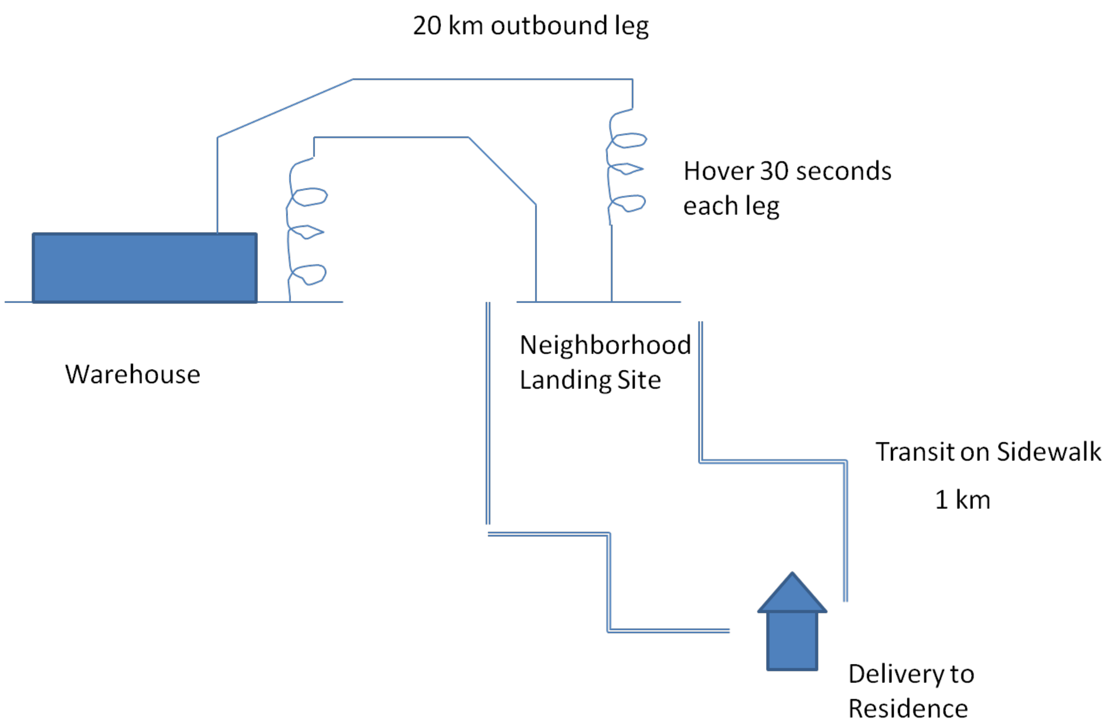


Fig. 2 – MICHAEL Mission Profile

Among the potential neighborhood VTOL landing sites for the MICHAEL mission are municipal parks, nearby office or retail building rooftops, etc. The above notional MICHAEL mission profile is not optimized on the basis of a detailed package-delivery network analysis/simulation. Instead it is a generic profile provided so as to define some reasonable or plausible mission requirements for vehicle conceptual design discussion later in the paper.

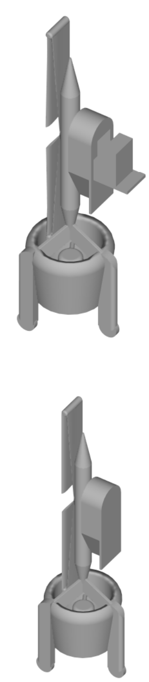
The key element of the MICHAEL concept – versus the point-to-point (warehouse-to-backyard) delivery drone concepts – is the ground mobility phase of the MICHAEL mission. The required ground distance to be traveled and the average ground speed attained will both substantially impact the relative productivity and overall success of the MICHAEL concept. The more time spent on the ground, versus the air, will reduce the greatest advantage of delivery drones versus automotive (truck or van) delivery: time-to-delivery to the consumer.

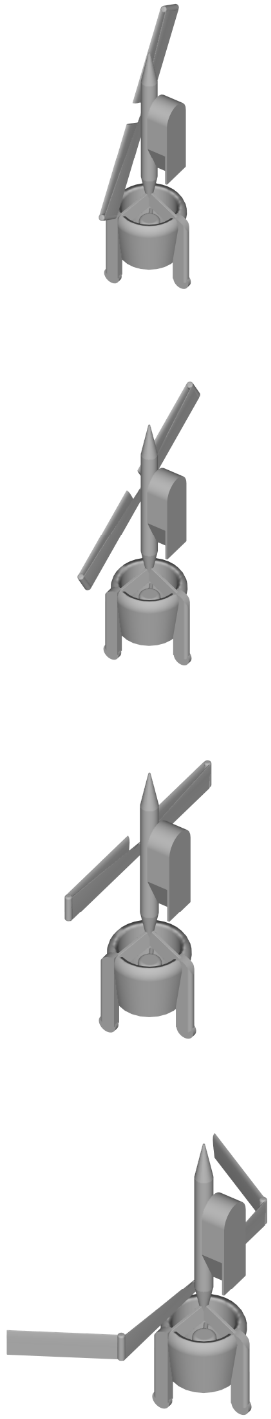
Notional Baseline Vehicle:

"Roadable" aerial vehicles have been proposed for decades, continuing to this very day (Ref. 9). And, yet, except for a small number of proof-of-concept vehicles, roadable vehicles have yet to be successfully developed. Despite this mixed development history, however, it may be quite possible to develop a small (<90kg or <200 lb_f) vehicle that travels at a relatively low speed (<16kph or <10 mph) on bicycle paths or sidewalks versus the far more challenging design problem of larger passenger-carrying vehicles that operate on roadways.

The MICHAEL robotic multimodal platforms are also a good mission application test case for the implementation of all-electric or hybrid-electric propulsion for small VTOL aerial vehicles. Hybrid-electric propulsion has recently gained a considerable amount of interest within NASA, including its application to rotorcraft (Ref. 9). A small electric propulsion UAV is a far more tractable problem than a larger passenger-carrying vehicle.

Figure 3 illustrates one notional MICHAEL configuration; Fig. 3 is a set of "time sequence" images showing the vehicle in its ground-mobile (with folded/stowed wings) form, followed by it unfolding/unstowing its wings prior to and during takeoff. The baseline MICHAEL configuration shown in Fig. 3 is a ducted-fan tailsitter vehicle. Upon vertical takeoff, the vehicle would pitch forward with increasing forward speed and transition to level-flight cruise mode. A variety of means of successfully trimming the vehicle pitching moment throughout transition can be devised. Among those methods are the use of vanes with flaps within the duct – and within the rotor downwash – so as to provide the required control moment authority. The baseline MICHAEL vehicle employs a set of fixed-pitch coaxial rotors within the duct.





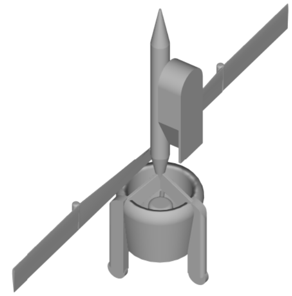


Fig. 3 – Notional Transformation of Roadable Ground Vehicle to a "Tailsitter" VTOL Aerial Vehicle

As a ground mobile system, the MICHAEL vehicle begins to incorporate attributes of the 'service robot' application domain – i.e. it is, in effect, a robot that closely interacts with human beings in their (the human's) living environment (Ref. 11). This is highly unconventional, nontraditional way of looking at aerial vehicle design and missions.

In pursuing this notion of a delivery drone as a service robot, this leads to the vehicle "form" being inspired, in part, by the 'service robot' function and not purely on aerodynamic performance considerations. The vehicle baseline tailsitter design is very compact and has a vertical orientation when both landed and ground-mobile which is, further, roughly physically scaleable with a human's stature/footprint and is, therefore, consistent with the vehicle acting as a service robot in a social interaction.

An alternate MICHAEL-like concept that has been previously studied at NASA Ames Research Center has been the use of a VTOL aerial vehicle to transport and deploy (once on the ground at the neighborhood landing site) an independent ground-mobile robotic system for final package delivery. The ground-mobile robot would in effect be "cargo" for a utility-type rotary-wing aerial platform.

There are also many analogous aspects of the MICHAEL delivery drone concept with respect to urban metro/regional aerial transportation concepts (Refs. 6-8): i.e. low-altitude flight over urban/suburban areas, the use of all-electric or hybrid-electric propulsion for community friendliness as to emissions and noise, the employment of high-levels of autonomous system technology, and the extremely complex nature of the air traffic management problem with respect to the coordination of hundreds to thousands of autonomous aerial vehicles safely interacting with manned aircraft.

System Analysis of Mission Tradeoffs between Ground- and Aerial-Mobility

MICHAEL delivery times will fall somewhere in between delivery times for ground transportation deliveries by means of automotive platforms (with or without drivers) and the warehouse-to-doorstep aerial transportation model that has to-date been the default paradigm for most small package delivery drone concepts.

Early work on this problem was performed in Ref. 1. In that early work, the potential for small autonomous aerial vehicles was identified. The follow-on question for this current work is what magnitude of compromise in time-to-delivery is accepted if a point-to-point air delivery was substituted by the MICHAEL CONOPS model wherein multimodal air and ground mobility were used for package delivery?

Figures 4-5 introduce the concept of ciruituity of distance traveled by air- and ground mobile systems – with emphasis of delivery drones versus automobile/truck deliveries. Circuituity will be a key parameter for the system analysis to follow. Note that because of the low altitude and extremely short ranges of vehicle travel, that a straight line approximation can be made in the system analysis and discussion that follows. The straight line approximation can be used instead of having to consider in more detail ascent and descent profiles and great circle, etc., flight paths typically required for the analysis of conventional aircraft in air traffic management simulations.

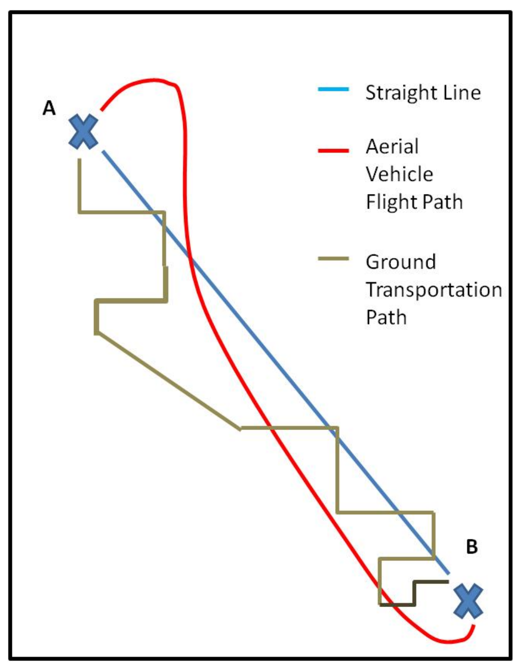


Fig. 4 – Ground versus Aerial Vehicle Point-to-Point Path "Circuituity"

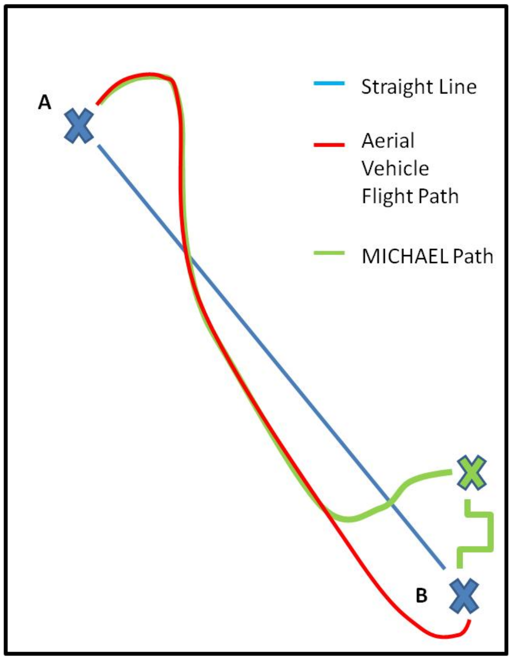


Fig. 5 – Notional Comparison between Point-to-Point Aerial Flight Path and the MICHAEL Flight/Ground Path

The initial system analysis performed in this paper looks at two aspects of the problem, for the various delivery options (ground/truck, pure aerial vehicle point-to-point, and the MICHAEL multimodal mobility): energy expenditure and time.

Relative energy expenditure is assessed between automobile/truck versus pure point-to-point aerial vehicle package delivery for a prescribed nominal travel distance (42 km) in Fig. 6. As expected, the energy expended by an automobile or truck is significantly larger than an equivalent distance flown by a small aerial vehicle.

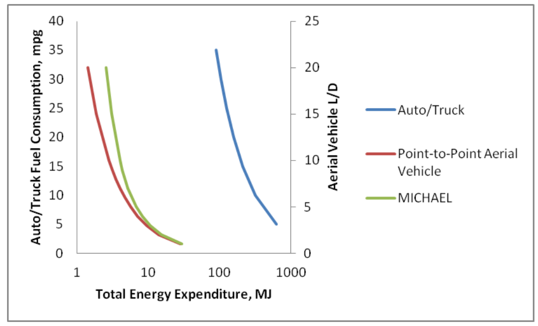


Fig. 6 – Relative energy expenditure

A "breakeven" analysis is now provided whereby an assessment is made of the maximum number of flights required (one package at a time) that would have to be flown to breakeven with the overall energy expenditure of delivery by automobile or truck. The truck performance is assumed to be only secondarily affected by the number of packages onboard the truck. A delivery truck would typically carry 100-300 packages. As can be seen in Fig. 7, depending on the fuel milage of the delivery trucks and the L/D of the competing delivery drones, this breakeven number of packages can range from just over ten packages to close to 200 packages. Vehicle L/D has, not surprisingly, a significant effect on this breakeven package count estimate. Providing a high L/D for a VTOL platform has historically been a challenge; this challenge is compounded when considering including "roadable" capability. Nonetheless, such a challenge is potentially addressable with new technologies and innovative vehicle designs. But even with a high L/D, the results of Fig. 7 (and earlier work in Ref. 1) would suggest that delivery drones will primarily be focused on small, time critical, and high-value packages instead of bulk shipments of low-value items.

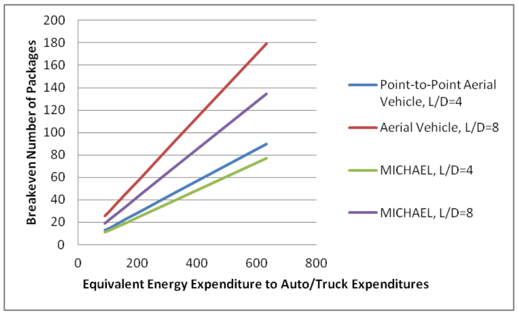


Fig. 7 – "Breakeven" number of flights to expend the same amount of energy as an automobile/truck

Next the relative energy expenditure is assessed of a multimodal mobility delivery approach (i.e. MICHAEL) as a function of the ground travel ratio, G, in Fig. 8. If G=0, then a pure point-to-point aerial vehicle delivery is assumed. Nonzero values of G imply some level of multimodal mobility. G=1 is a fully ground-mobile system (though at reduced energy expenditure as compared to an automobile or truck given the vehicle's lightweight and all-electric nature). Additionally, with G=1 there is a step change in energy expenditure in that hover and an inflight reserve are no longer required. The energy expenditures are predicated on a 42 km total mission range.

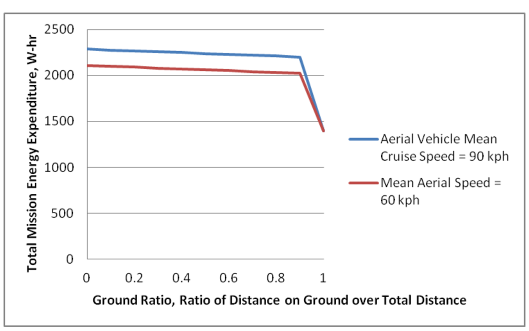


Fig. 8 – Energy Expenditure as a function of Ground Travel Ratio, G

Delivery time is now considered instead of energy expenditure. First, relative time saved between an automobile/truck package delivery (for one package at some prescribed nominally distance) is compared to the delivery times for a pure point-to-point aerial vehicle for various assumed vehicle speeds and circuituity levels. The auto/truck estimates do not account for delays due to intersection lights, traffic, or multiple package deliveries.

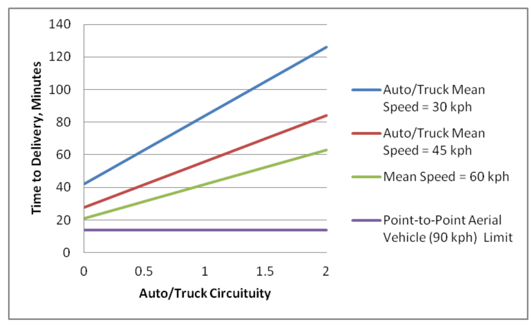


Fig. 9 – Time-to-delivery Tradeoffs between Auto/Truck and Point-to-Point Aerial Vehicle

Finally, the relative time saved between a pure point-to-point aerial vehicle versus a multimodal mobility vehicle (i.e. MICHAEL) is assessed as a function of G, the ground travel ratio. The below time to delivery estimates assume that the vehicle flies at a cruise speed of 90kph and moves on the ground at speed of 15kph. The warehouse package preparation and launch time is not factored in the delivery estimate. Additionally, delays on the ground due to roadway intersection crossing and traffic congestion are also not factored in to the delivery time estimates.

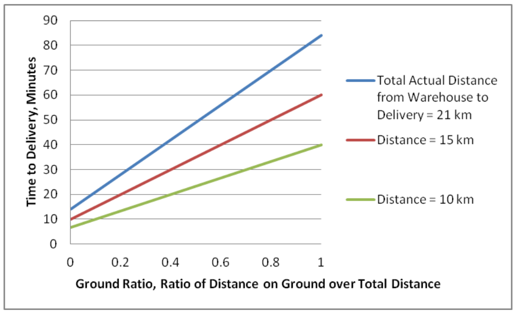


Fig. 10 – Time-to-delivery as a function of G, ground travel ratio

Ultimately, this simplified type of system analysis needs to be superceded by local airspace simulation modeling. This level of analysis, though, can be used to guide both MICHAEL vehicle design as well as develop network designs for neighborhood landing sites.

Cargo Delivery "Drone" Trade Space Examination

There are many different rotary-wing and VTOL aerial vehicle configurations that could be relevant to the MICHAEL mission design requirements and CONOPS. The ducted-fan tailsitter configuration introduced earlier is just one possible configuration – other potential configurations include a whole gamut of multi-rotor configurations, including distributed, modular, and heterogeneous rotor systems (Ref. 4). Other VTOL concepts of merit include versions of autonomous aerial vehicles studied in Refs. 2 and 3 and, perhaps, smaller versions of the electric VTOL vehicles ("Hoppers") explored in Refs. 6-8. Nonetheless, the ducted fan tailsitter is adopted as a baseline configuration for the remainder of the discussion in this paper primarily of its compactness and maximum cruise speed capability.

A well-known graphical means of showing the global design trade space of VTOL vehicles is the "wheel of V/STOL aircraft and propulsion concepts" (Ref. 12). An analogous "wheel of delivery drones" is proposed and presented below in Fig. 11 to help foster a global understanding of the design trade space of this emerging application domain.

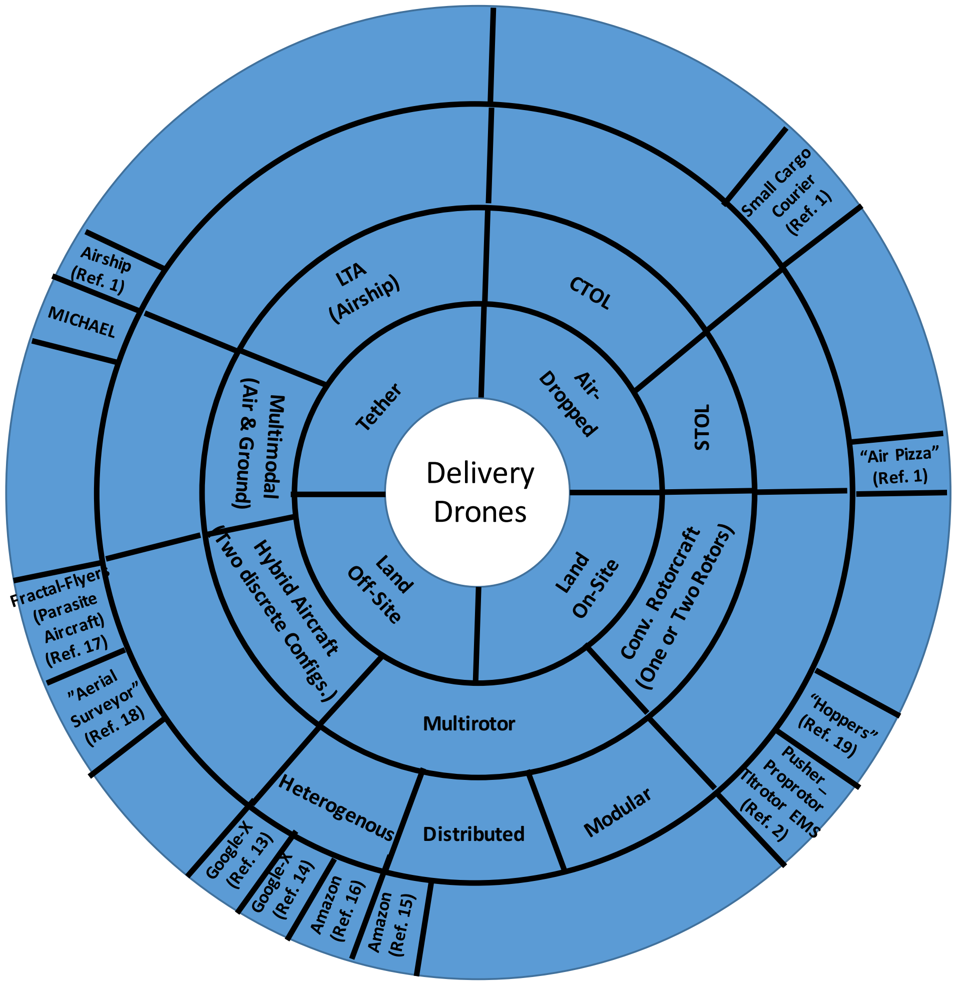


Fig. 11 – Wheel of Delivery Drones

Using a conceptualization device such as the Fig. 11 "wheel of delivery drones" provides not only a convenient way to summarize past work in this technical area but, through gaps or empty sectors in the wheel, it also provides insight into possible future design approaches to explore. The MICHAEL concept has been included on the Fig. 11 "wheel of delivery drones."

One key secondary design attribute for delivery drones is, as noted earlier, hybrid electric propulsion. Internal combustion engines might possibly be employed for in-flight cruise propulsion whereas electric propulsion might be used for takeoff and landing and, as well, ground mobility (especially near residences or, even more so, if used for mobility inside commercial properties or buildings). There is a spectrum of hybrid-electric propulsion options for small cargo delivery drones such as MICHAEL. This hybrid-electric design trade space will undoubtedly foster novel technical insights.

Another secondary design attribute being debated between delivery drone proponents is the exact method of final delivery of packages. In particular, some proponents believe the package should lowered to the ground via a reelable tether that can be deployed from the vehicle hovering some distance above the ground (Refs. 13-14). Alternatively, some proponents believe the package should be deployed from the vehicle while it is stationary on the ground (Refs. 15-16). And, finally, some proponents believe an air-drop would be the best method of delivery. In some cases, the type of aerial vehicle being considered automatically dictates which final delivery method is employed: e.g. a small lighter than air (LTA) airship – because of its comparatively large volume/size – cannot closely approach the ground and would have to deploy packages via a tether or air-drop; alternatively, a conventional takeoff and landing aerial vehicle (because of inadequate available landing area) would likely have to precision air-drop packages.

Baseline MICHAEL Vehicle Concept Definition

Table 1 summarizes some high-level notional mission/design requirements for the baseline MICHAEL conceptual design.

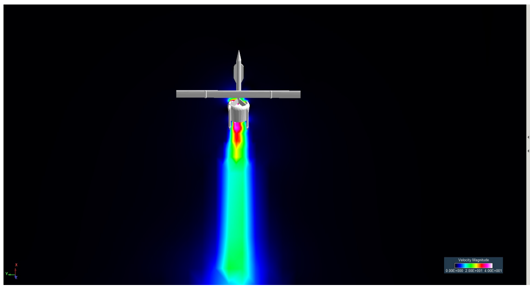
Table 1 – Conceptual Design Requirements

Requirements	
Max. Payload/package Mass (kg)	2.5
Max. Payload/package Dimensions (cm)	30x30x30
Total Flight Range (km)	40
Total Hover Duration (min.)	2
Reserve (in cruise, min.)	10
Max Cruise Speed (kph)	90
Cruise Altitude, AGL (m)	120
Total Ground Distance (km)	2
Max Ground Speed (kph)	15
Max. Terrain Grade (Deg.)	10
Max. Surface Unevenness (cm)	1
Braking distance at max. ground speed (m)	3
All-Electric propulsion	Ground & Air
Max. Dimension of Vehicle Footprint (m)	1
Max. Vehicle Height (m)	2.2

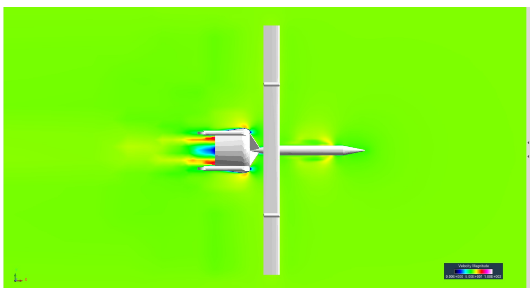
The vehicle height and max footprint dimensions are defined to be consistent with the ability of the vehicle to operate within the entrances and interiors of residences and office buildings.

Aerodynamic Design and Analysis

The rotorcraft computational fluid dynamics software tool RotCFD is being used to perform initial studies of the aerodynamic characteristics of the baseline MICHAEL vehicle.

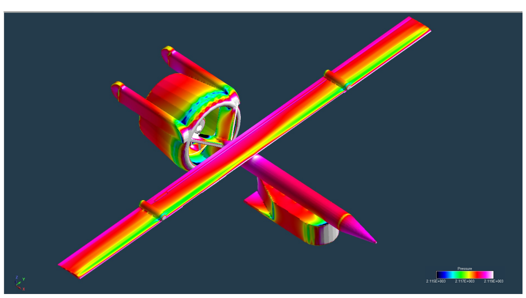


(a)



(b)

Fig. 12 – MICHAEL: (a) Hover and (b) Cruise flow field predictions



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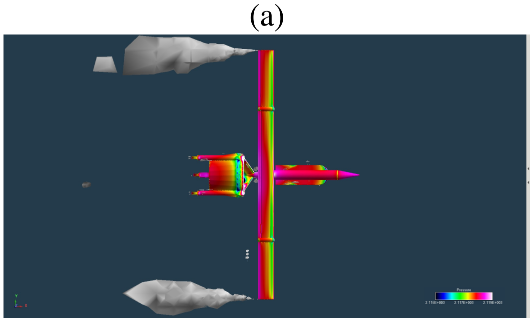

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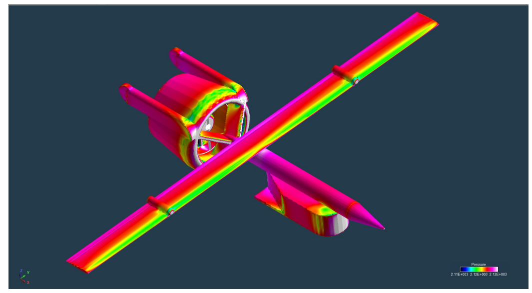

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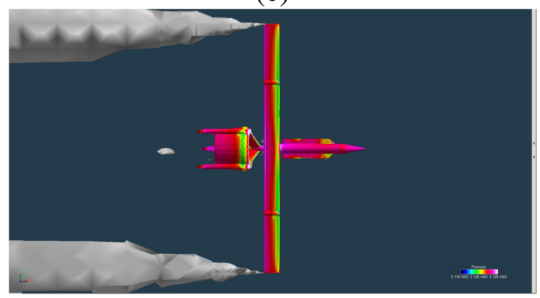

(d)

Fig. 13 – Body Surface Pressure Distributions (top view) as a function of Angle-of-Attack: (a) and (b) AOA=3 and (c) and (d) AOA=7

Initial predictions were made at a forward-flight speed of 50 ft/s (or ~34 mph or ~55 kph). This speed should be considered the lower bound of the tailsitter conversion/transition from lift being provided primarily from the propellers to fixed-wing-borne flight. As noted in Table 1, the target design maximum cruise speed is 90kph. The reference area used for the vehicle coefficients is the wing area which is 5 ft^2 or 0.47 m^2 (note that the reference area does not include any of the duct "planform" area, even though the duct is carrying net lift in forward flight). The wing span is 8.9 ft or 2.7 m and the wing chord length is 0.56 ft or 0.17 m. The predicted vehicle lift coefficients are indeed as high as they are because a significant portion of the vehicle lift (or perhaps more properly net vertical force) in cruise comes from duct and the payload fairing contributions (as can be seen by the body surface pressures shown in Fig. 13) – but, of course, at the cost of very high drag levels with the current design.

Fig. 14 – Lift Coefficent versus Angle-of-Attack of Baseline Vehicle

The predicted drag is quite large because of a number of factors. First, the baseline design's duct employs a rather thick, cambered airfoil. Second, the external payload fairing (in which the small package to be delivered is contained) in the current baseline design is approximately 37% thick, a very low finite-span aspect ratio of 0.24, and only roughly airfoil-like in geometry; as can be seen in Fig. 13(a) and (c), there is a significant amount of pressure drag due to surface pressures at the leading and trailing-edges of the payload/package fairing. The splitter plane below the payload fairing helps moderate some of that pressure drag but it appears that this is an area for design improvement. Third, support vanes attaching the main fuselage with the duct show elevated levels of positive pressure on their leading-edges. Fourth, and finally, a rather bluff cylindrical body is used in the CFD model to represent the housing notionally containing the (electric) motors driving the vehicle propellers; this bluff body also has a significant pressure drag contribution to the overall vehicle's drag predictions. The above issues will be addressed in subsequent design iterations and modeling refinements.

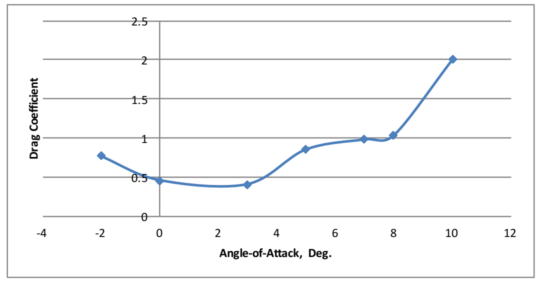

Fig. 15 – Drag versus Angle-of-Attack of Baseline Vehicle

The lift-to-drag ratios currently predicted for the current baseline design are very modest.

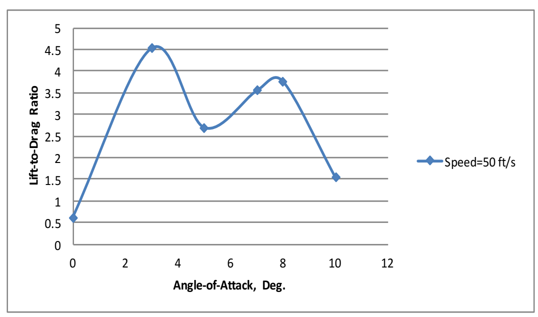

Fig. 16 – Lift-to-Drag Ratio as a function of Angle-of-attack

These aerodynamic analysis results were factored into the vehicle sizing analysis discussed in the next section of the paper.

Vehicle Sizing

Vehicle sizing of a roadable vehicle is unlike that of a conventional aircraft. Vehicle sizing of a VTOL vehicle acting, in part, as a socially interactive service robot is even more unconventional. The initial focus should first be on defining and sizing the ground-mobile subsystems of the vehicles (Fig. 17). Secondly, after the ground mobile elements have been initially sized then the second set of subsystems to be defined and sized is the wing(s) – and/or (as appropriate) rotor(s) – folding/stowing mechanisms. Only then, after that these initial critical subsystem sizing efforts, can sizing be performed on the aerial vehicle itself.

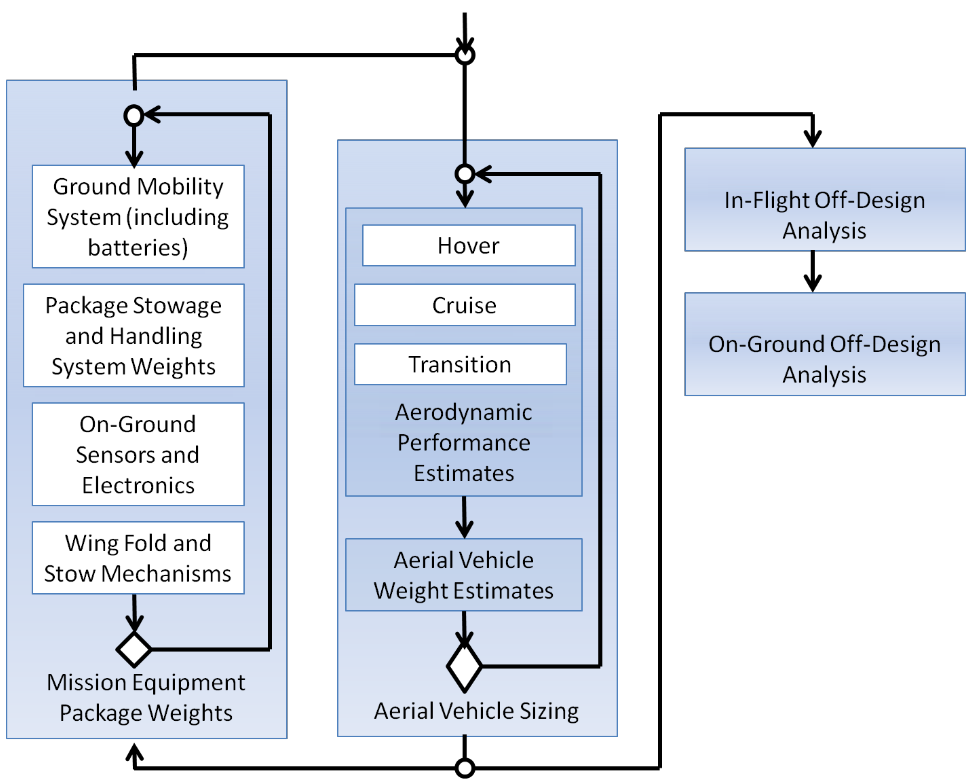

Fig. 17 – MICHAEL Vehicle Sizing: Treating "Roadable" and Package Handling Subsystems as a "Mission Equipment Package"

The first-order vehicle sizing analysis performed herein is not based on a clean-sheet paper airplane exercise. This initial analysis effort has been very much informed by available COTS mechnical and electric components readily available for the proof-of-concept and prototyping work discussed later in the paper. Accordingly, non-optimal components result in a heavier, less efficient, and nominally less capable vehicle than what is theoretically achievable with a clean-sheet approach. The advantage of the current approach, though, is that it is less dependent on statistical or historical data and regression-analysis weight equation approach for vehicle components and subsystems. This is particularly an important consideration in that regression-analysis-based weight equations don't exist for subsystems such as the ground mobility and wing fold/stow elements.

Overall duct size is a key consideration in the MICHAEL design. Sizing of the duct is primarily driven by three factors: first, propeller size (driven, in turn, by the VTOL requirement) drives the duct diameter, second, the necessity for the duct and it's nominal airfoil thickness is driven by safety considerations (to protect the propeller blades and, in turn, people and property from damage if the rotating or nonrotating blades collide with anything) and, third, the incorporation of the ground-mobility propulsion subsystems requires a structurally robust and stiff duct to be mounted to or otherwise support. Additionally, there are secondary considerations such as duct size and geometry influencing propeller static thrust aumentation. As already seen from discussion of initial baseline design CFD results, though, the duct is a significant contributor to both vehicle lift and drag. Future design iterations will have to look closely at whether the duct is oversized with respect to meeting its ground-mobility and safety requirements and whether it might be possible, accordingly, to be reduced in size and otherwise slimmed down (such as using less cambered and thinner airfoils).

The baseline design looks tail-heavy because of the large duct. Mass balancing would be achieved by locating the large mass of batteries as far forward along the vehicle longitudinal axis as possible. Additionally, the primary wing will have a mechanism to translate/traverse the wing along the longitudinal axis so that the aerodynamic center is made coincident with the center of gravity. Figure 18 schematically illustrates a notional layout of key subsystems for the vehicle. This layout assumes an all-electric propulsion system for the vehicle. Later design iterations may well consider a hybrid-electric system (where a small piston-based internal combustion engine (ICE) either direct-drives the propellers in cruise or, alternatively, this ICE drives a generator that then feeds current to the propulsion electric motors, i.e. a "range extender" type system, e.g. Ref. 19).

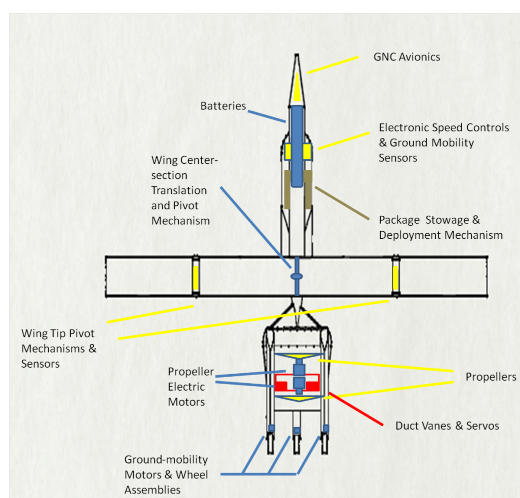

Fig. 18 – MICHAEL Baseline Design Subsystem Overview Schematic

Tables 2 and 3 summarize the current first-order sizing of a MICHAEL vehicle. Table 2 summarizes the vehicle geometry and aerodynamic characteristics and Table 3 summarizes the weight breakdown estimates or measurements (in the case of actual COTS hardware being employed). The below tables do not represent a optimized point design but rather a work-in-progress assessment of a proof-of-concept vehicle.

Table 2 -- MICHAEL Vehicle Geometry and Aerodynamics Characteristics

Parameter	**Value**
Wing/duct airfoil	NACA 4412
Primary wing span	2.71 m
Primary wing constant chord	0.17 m
Vehicle Cruise L/D	4
Coaxial propeller cruise effective efficiency	0.9
Coaxial propeller static thrust figure-of-merit	0.6
Duct fairing diameter	0.73 m
Duct fairing length	0.39 m
Number of (2-bladed) propellers	2
Propellers diameter	0.69 m

Table 3 -- MICHAEL Vehicle Weight Breakdown

Component/Subsytem	**Weight (kg)**
Payload Capacity	2.5
Avionics and Sensors	0.5
Batteries (Li-Ion; 150 W-hr/kg)	15.2
ESC for propeller and wheel motors (QTY 5)	0.31
Fuselage structure	3.2
Primary wing structure	1.6
Duct Fairing, Vanes, Legs	7.0
Vane servos	0.25
Wing fold, pivot, and traverse servos	0.5
Propellers (QTY 2)	0.54
Propeller electric motors (QTY 2)	2.6
Wheel gearmotors (QTY 3)	2.39
Wheels (QTY 6)	1.12
Total =	37.7

Note that it would have been perhaps desirable to have the vehicle weigh at or less than the current FAA commercial UAV weight limit of 25 kg but this is not perceived as a hard design requirement. The vehicle sans batteries does weigh less than 25 kg. To complete the mission profile summarized in Table 1 the vehicle has been estimated by means of first-order analysis to weigh approximately 37.7 kg, with 15.2 kg of batteries.

System Sensors & Controls

A rudimentary control perspective is offered below as to distinct mission phasess for the MICHAEL platform: ground mobility; conversion from ground to aerial vehicle configuration (wing folding/stowing); hover; low-speed transition from hover to cruise forward flight; cruise. During each of these distinct mission phases there will be a different subset (though sometimes overlapping) of sensors, controls, and control laws required for those mission phases. This is summarized in Tables 4-6 immediately below.

Eliminating unneccesary redundancy of subsystems will be a key challenge to reduce overall vehicle weight and, consequently, the viability of a small roadable aerial vehicle. Table 4 summarizes the anticipated sensors and controls required for the ground mobility phase of the MICHAEL mission. Table 5 summarizes the sensors and controls required for conversion from ground mobility configuration of MICHAEL to its aerial configuration, including the critical elements of the wing unfolding, pivoting, and translating. Table 6 summarizes the sensors and controls for VTOL takeoff and landing, tailsitter transition from vertical to horizontal orientation, and cruise. Tables 4-6 identifies the sensors and controls, indicates their purpose, notes potential dependencies with other sensors and controls and notes their potential priority to safely and effectively accomplish the overall mission. Table 4 is unique to roadable aerial vehicles. Several sensors and controls are unique to roadable aerial vehicles.

Table 4 – Sensors/Controls Required for Ground Mobility

#	Descrip.	Purpose	Depend-ancies	Priority (1,2,3)
S1	Kinectix	Indoor Visual Nav.		2
S2	wifi	Package Exchange		2
S3	Ultrasound	Indoor Forward Prox.Sensor		2
S4	Thermistor	Motor Temp.	C1	3
S5	Thermistor	Motor Temp.	C2	3
S6	Thermistor	Motor Temp.	C3	3
S7	Current	Wheel 1 Motor	C1	3
S8	Current	Wheel 2 Motor	C2	3
S9	Current	Wheel 3 Motor	C3	3
S10	Contact Sensor	Package hatch in Payload Fairing		2
C1	E-motor	Wheel 1 Drive	C1, C3	1
C2	E-motor	Wheel 2 Drive	C1, C3	1
C3	E-motor	Wheel 3 Drive	C1, C2	1
C4	E-brake	Wheel 1		2
C5	E-brake	Wheel 2		2
C6	E-brake	Wheel 3		2
C7	Linear Actuator	Package Hatch Open/Closed		2

Table 5 – Sensors/Controls Required for Conversion from Ground to Aerial Vehicle

#	Descrip.	Purpose	Depend-ancies	Priority (1,2,3)
S11	IMU	GNC		2
S12	GPS	Outdoor Nav.		1
S13	Rotor 1 RPM	Failsafe: C1, C2, C3 Disabled		1

		when nonzero		
S14	Rotor 2 RPM	Failsafe: C1, C2, C3 Disabled when nonzero		1
S15	Contact Sensor	Failsafe: Wing Tip 1 Folded	C1, C2, C3	3
S16	Contact Sensor	Failsafe Wing Tip2 Folded	C1, C2, C3	3
S17	Contact Sensor	Failsafe: Wing Center-section Pivoted Closed	C1, C2, C3	3
S18	Current	Wing Tip 1 Servo		
S19	Current	Wing Tip 2 Servo		
S20	Current	Wing Center-section Pivot Servo		
S21	Current	Wing Center-section Translation Motor		
C8	Servo	Wing Tip 1 Pivot		
C9	Servo	Wing Tip 2 Pivot		
C10	Servo	Wing Center-section Pivot		
C11	E-motor	Wing Center-section Translation		
C12	Solenoid	Wing Tip 1 Lockout Pin		
C13	Solenoid	Wing Tip 2 Lockout Pin		
C14	E-brake	Wing Center-section Pivot Lockout		
C15	Solenoid	Wing Center Translation Lockout Pin		

Table 6 – Sensors/Controls Required for Aerial Vehicle Flight

#	**Descrip.**	**Purpose**	**Depend-ancies**	**Priority (1,2,3)**
S22	LIDAR	Nadir Visual Nav. for Landing		1
S23	Potentio-meter	Duct Vane 1 Position		1
S24	Potentio-meter	Duct Vane 2 Position		1
S25	Potentio-meter	Duct Vane 3 Position		1
S26	Inclinometer	Vehicle Orientation (100 Deg. Range)		1
C16	Servo	Duct Vane 1 for Trim		1
C17	Servo	Duct Vane 2 for Trim		1
C18	Servo	Duct Vane 3 for Trim		1
C19	E-motor current; ESC	Drive propeller 1	S13 and S14	1
C20	E-motor current; ESC	Drive propeller 2	S13 and S14	1

As can be seen in Tables 4-6, in many cases similar sensors are used during different multimodality phases of the vehicle's mission. For example, a LIDAR system or an imaging camera could have great utility during both the in-flight and the gorund mobility phases of the mission. However, bcause of the different requirements for both mission phases (LIDAR and camera aligned with the vehicle's longitudinal axis for in-flight and along a lateral axis when ground mobile), either separate and indepedent sensors might have to be used or some sort of repositioning and focusing mechanisms might need to be implremented to use the same set of sensors for the two different mission phases.

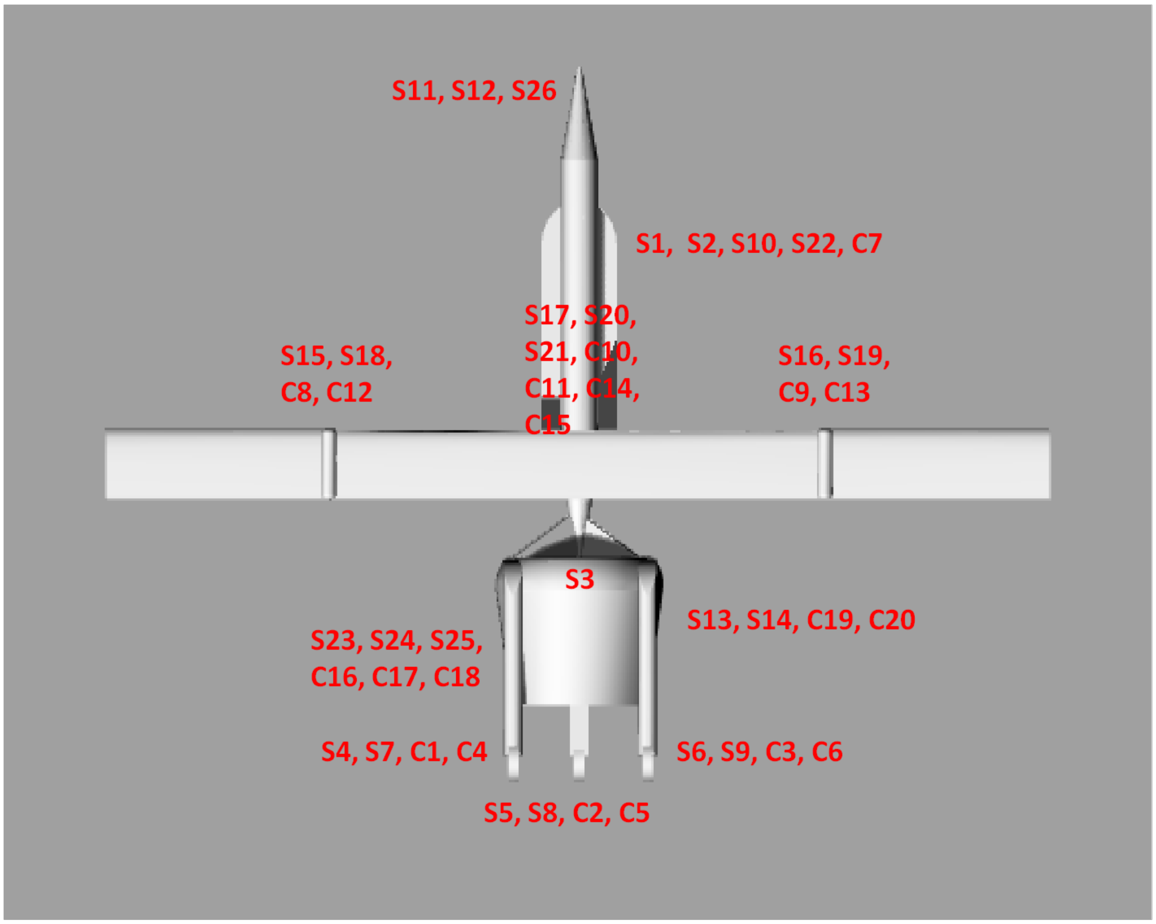

Fig. 19 – Overall Vehicle I/O Sensor/Controls Schematic

Initial Proof-of-Concept and Prototyping Activities

The body of proof-of-concept work is focused on vehicle prototyping. Appropriately so, proof-of-concept work to date has focused on using 3D printing additive manufacturing as a first-choice integral part of the design/development process (Fig. 20).

One of the advantages of using 3D printing for the development of the MICHAEL proof-of-concept test articles is that it potentially allows for a future open source approach for other research teams that might want to build upon the MICHAEL concept and the design work performed to date. MICHAEL was originally conceptualized as a student intern engineering project. Use of 3D designs and 3D print files potentially allows for an easy "handoff" to successive student teams for future work on the overall MICHAEL concept.

Large COTS clockwise- and counterclockwise-rotating propellers (27 inch, or 0.69m, diameter) are currently being used for the proof-of-concept test article development, Ref. 26. Correspondingly, COTS multirotor compatible electric motors are being used as the primary propulsion system for the coaxial propellers.

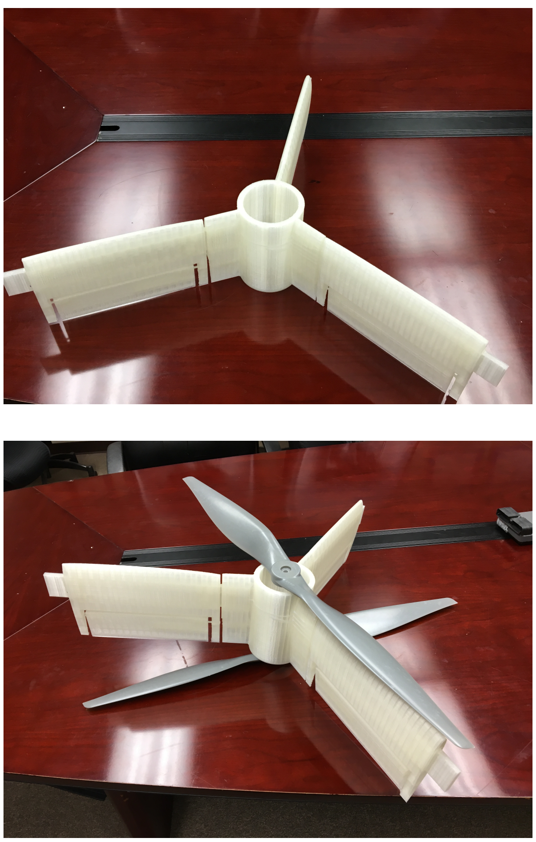

Fig. 20 – Proof-of-Concept Test Articles (in-development)

Two of the major downsides of attempting to use 3D printing for small aerial vehicle prototyping is that, first, it does not necessarily result in the most weight-effcient solution to aircraft structures and, second, the strength of the resulting components is not necessarily on par with other fabrication approaches and materials. In this regards, use of 3D printing was embraced more because of its design/development flexibility and fabrication convenience than weight and strength considerations.

Ground Mobility

It has been asserted in this paper that the design of a MICHAEL vehicle should first start from the premise that the system is a service robot first and an aerial vehicle second.

Wheel count and the number of electric motors required for ground mobility is a very important set of design questions. Commercially demonstrated technologies already exist that allow wheel counts to range from one to greater than four wheels. One and two wheel/motor cofigurations require gyroscopically balanced control systems for the ground mobility subsystem. The minimal wheel count for a passively stable wheeled system is three wheels. Additionally, creative wheel designs stemming from the consumer robotics market are increasing the inherent flexibility for precision positioning of wheeled vehicles/robots. The baseline MICHAEL design would use a tripod support with three wheels, each driven by an electric gearmotor with a rightangle output, each terminating with a pair of Vex robotics-kit wheels (in the particular case of the proof-of-concept work reported in this paper this would be sets of 4-inch Mecanum wheels; Ref. 20). Refer to Fig. 21. A simpler alternate to the baseline design would be to use a non-motor-driven "tail dragger" type wheel assembly for one of the three wheel assemblies; however, for precision positioning capability in confined spaces such as might exist for MICHAEL deliveries in office spaces this alternate was not incorporated into the baseline design. The electric motors for the MICHAEL design are of the same class of motors used for comparable applications such as automotive, large robots, electric bicycles, electric golf carts, and electric wheel chairs: i.e., DC electric motors with reasonably low mass, low rpm output, and high-torque capability.

Fig. 21 – Initial Wheel Assembly Layout

Wing Folding/Stowing

A reliable and robust actuated wing folding/stowage subsystem has long been a not completely resolved technical issue for "roadable" aerial vehicle concepts. Advances in materials and actuators are making this problem more tractable than it has been in the past but it is still nonetheless challenging. What makes this somewhat more viable than the personal air vehicle "flying car" design efforts of the past is that the MICHAEL vehicle is intentionally defined as being a small (<200lbf or <90kg mass) vehicle that travels along the ground at slow speeds (<10 mph or <16 kph). Consequently, it is anticipated that the loads and, therefore, overall vehicle structure and propulsion requirements are more manageable design-wise.

The baseline MICHAEL vehicle conceptual design in Fig. 3 illustrates one specific approach to the wing fold/stow problem. The proposed unfolding/unstowing process is as follows: 1. the folded/stowed wing assembly swings from a vertical orientation (along the fuselage longitudinal axis) to a horizontal orientation; 2. the wing assembly pivot point traverses downward from aproximately midway along the fuselage axis to just above the ducted fan lip (coincident with the assumed c.g. of the vehicle); 3. two outboard wing fold sections unfold at discrete hinge lines to slowly align themselves with the center-span wing section; 4. once aligned, lockout pins are engaged and the unfolded wing assembly forms one continuous large aspect-ratio wing structure; 5. the above unfolding and unstowing process is reversed (i.e. folding and stowing) just prior to the ground-mobility phase of the mission. Note, though, that the above is just one possible approach to the general wing fold/stow problem.

The are two polar extremes of mechanically actuating the wing fold/stow process. At one extreme, each wing degree-of-freedon would require a minimum of one actuator, servo, or electric motorr and one lock-out mechanism (a solenoid driven pin or electric brake, etc.). Add in, as needed, redundancy and the result is a fairly high component count. The degree of freedom count for the baseline MICHAEL design is four degrees of freedom: two wing folds (of the outer tip span sections of the wing) and wing center section pivot and its longitudinal axis translation. The component count for a non-redundant acutation sytem for the baseline MICHAEL design would be: four actuators/servos/motors and four solenoid-driven-lockout-pins/electirc-brakes. The sizing (mass and power) of these actuators and lockout mechanisms can be moderated somewhat by creative mechanical design and tailoring of the fold/stow process so as to minimize actuation forces and moments. On the other extreme, it is possible to rely mostly on passive deplyment for the wing folding and stowing. This could be accomplished by the use of springs, wing section center of gravity tailoring, gravity loads, and use of inerital loads stemming from aceleration/deceleration of the vehicle/wing due to spinning or rocking backwards and forwards the vehicle by its electric-motor-drive wheels. Additionally, the necessity for lockout pins could be somewhat alleviated by tailoring the direction of wing unfolding/folding. The key determining factors for the wing fold/stow mechanical subsystem design approach are reliability, robustness, mechanical system complexity, and mass, power, and cost. A mostly passive design that is unreliable or prone to failure is not viable irrespecitve of its conceptual simplicity; on the other hand, a very reliable and robust system that weughs too much or draws too much power is also unacceptable.

(Service) Robotics

MICHAEL needs to closely interact with people during the final stages of the package delivery, to navigate amongst people within their neighborhoods, to operate in close proximity to and maybe within residences and businesses. It is this social interaction, among other things, that makes the MICHAEL vehicle/system quite different from a conventional autonomous aerial vehicle.

Designing a socially interacting service robot is still an ongoing area of research for robotists (Ref. 11). To illustate the robotics challenge underlying the MICHAEL concept a relatively simple social interaction task is now described: the final delivery of the package itself. Assume for the moment that the package is to be directly delivered to a specific individual within a office work space. Among the many subtasks that might need to be performed to deliver the package are some of the following: 1. the robot must able to remotely ring/acess door bells, transit through open doorways and enter, exit and operate elevators; 2. the robot must be capable of indoor navigation to a predesignated dropoff point; 3. the robot must engage in hazard (furniture and people) avoidance when navigating indoors; 4. the robot would have to enter into communication exchanges or otherwise negotiate an authorization or signature for the package handoff; 5. an automated package release or deployment from the robot fuselage or chassis; 6. automated resealing or closure of the fuselage or chassis upon package delivery; 7. indoor navigation to back-track to and through the building exit. This list of subtasks is quite challenging even by state-of-the-art robotics standards. Further, this is just one task of several required to address the social interactivity required of MICHAEL as a service robot.

Finally, from a vehicle design perspective, there are interesting questions as to hazardous materials and fire hazards posed by a MICHAEL vehicle acting also as a "service robot" in close proximity to people and even operating inside dwellings and office-spaces. High-energy batteries and fuel-storage subsystems (for aerial vehicles having hybrid-electric propulsion) will have to be carefully considered in the context of public safety. Operation of such systems may require refinement of municipal building codes.

Beyond Cargo Delivery

As noted in the introduction of this paper, one of the high-level constraints of any proposed delivery drone transportation system concept is that not only does there need to be a compelling commercial business case made for such a system but it is asserted that it is also important that such systems are seen as providing secondary public services and/or community enhancements in addition to primary mission of commercial small package deliveries. There are many public service missions (Ref. 5) that have analogous mission profiles to the cargo delivery mission discussed in this paper.

Transportation provided by small autonomous aerial vehicles goes beyond just cargo or small packages. There is a whole spectrum of transporation that could nominally be provided by autonomous aerial vehicles (Fig. 22).

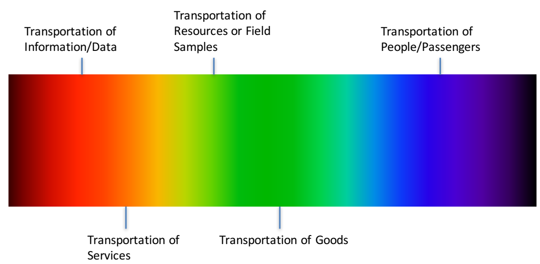

Fig. 22 – Autonomous Aerial Vehicle Transportation "Spectrum" Perspective

Potential Regulatory and Local/State Government Challenges

Regulations related to municipal parks, sidewalks, and bike lanes are all primarily under the purview of local governments. To enable MICHAEL systems using these municipal resources will require a concerted municipality-by-municipality corrdination effort.

There are many examples of open issues that need to be addressed for delivery drones including the requirements for all-weather operations, vehicle inflight power/fuel reserves, beyond-line-of-sight sensors for autonomous aerial vehicles flying at low altitudes (<120m AGL). Commercial operations of small VTOL UAVs are also currently limited by the FAA to under 25 kg; it is likely that a VTOL delivery drone with a total range of approximately 40 km will need to be larger than that weight limit. All of these considerations will likely need future FAA rulemaking.

Ancillary Benefits (and Challenges) of Implementing MICHAEL

Because of the ground mobility attribute of a MICHAEL vehicle, the result may be a cross-cutting expansion of wheel-chair and disability access to residences as well as expansion of bike-paths and lanes along or on roadways.

Because of the necessity for neighborhood VTOL landing sites for MICHAEL vehicles there could also be an expansion and/or improvement of public parks and facilities to accommodate not only their traditional usage but their potential dual-use for MICHAEL takeoff and landing.

Correspondingly, though, there will still be significant challenges to the introduction/adoption of MICHAEL cargo delivery.

Future implementation of a MICHAEL-based small package cargo distribution system would no doubt lead to a reexamination of community urban-planning concepts.

Future Work

The concept will be examined both computationally and also through system proof-of-concept prototyping. The mission CONOPS will also continue to be refined and assessed in detail.

Concluding Remarks

Delivery drones, roadable aircraft, and service robot assistants have each in their own way been considered to be "visionary" technologies that futurists have been anticipating for years if not decades. It is perhaps most appropriate that the promise of each of the above technologies might one day find their realization through a natural synergism resulting from their combined application. The MICHAEL concept – embodying all three general sets of technologies -- has considerable merit in addressing a number of socioeconomic pressures facing us in the future.

This work continues ongoing research investigations into "rotorcraft as robots." There is much promise but also much concern as to this ongoing fusion of intelligent systems, robotics, and aerial vehicle design: we have to be wise as much as we are smart. If we succeed, the outcome will be new knowledge, new services, and new capabilities that we could only previously imagine.

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References

1. Young, L.A., "Aerobots as a Ubiquitous Part of Society," AHS Vertical Lift Aircraft Design Conference, San Francisco, California, January 18-20, 2006.

2. Aiken, E.W., Ormiston, R.A., and Young, L.A., "Future Directions in Rotorcraft Technology at Ames Research Center," 56th Annual Forum of the American Helicopter Society, International, Virginia Beach, VA, May 2-4, 2000.

3. Young, L.A., Aiken, E.W., Johnson, J.L., Demblewski, R., Andrews, J., and Klem, J., "New Concepts and Perspectives on Micro-Rotorcraft and Small Autonomous Rotary-Wing Vehicles," AIAA 20th Applied Aerodynamics Conference, St Louis, MO, June 24-27, 2002.

4. Young, L.A., "Conceptual Design Aspects of Three General Sub-Classes of Multi-Rotor Configurations: Distributed, Modular, and Heterogeneous," Sixth AHS International Specialists Meeting on Unmanned Rotorcraft Systems, Scottsdale, AZ, January 20-22, 2015.

5. Young, L.A., "Future Roles for Autonomous Vertical Lift in Disaster Relief and Emergency Response," Heli-Japan 2006: AHS International Meeting on Advanced Rotorcraft Technology and Life Saving Activities, Nagoya, Japan, November 15-17, 2006.

6. Sinsay, J.D., Alonso, J.J., Kontinos, D.A., Melton, J.E., and Grabbe, S., "Air Vehicle Design and Technology Considerations for an Electric VTOL Metro-Regional Public Transportation System," 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, IN, September 2012.

7. Melton, J., Kontinos, D., Grabbe, S., Alonso, J., Sinsay, J., and Tracey, B., "Combined Electric Aircraft and Airspace Management Design for Metro-Regional Public Transportation," NASA TM-2014-216626, October 2014.

8. Alonso, J.J., Arneson, H.M., Melton, J.E., Vegh, J.M., Walker, C., and Young, L.A., "System-of-Systems Considerations in the Notional Development of a Metropolitan Aerial Transportation System: Implications as to the Identification of Enabling Technologies and Reference Designs for Extreme Short Haul VTOL Vehicles with Electric Propulsion," NASA TM (To be Published); draft report deliverable: https://www.nari.arc.nasa.gov/sites/default/files/Young_HopperII_NASA_TM15K.pdf

9. Russell, C.R.; Young, L.A.; Yamauchi, G.K.; Johnson, W.; Boyd, D.D.; Gorton, S.A.; Snyder, C.A.; and Kohlman, L.W., "Greener Helicopters," Encyclopedia of Aerospace Engineering, Eds. R. Blockley and W. Shyy, John Wiley, Chichester, DOI: 10.1002/9780470686652.eae1009, 12/29/2015.

10. Anders, S.G., Asbury. S.C, Brentner, K.S., Bushnell, D.M., Glass, C.E., Hodges, W.T., Morris, Jr., S.J., and Scott, M.A., "The Personal Aircraft – Status and Issues," NASA TM 109174, December 1994.

11. Fong, T., Nourbakhsh, I., and Dautenhahn, K., "A Survey of Socially Interactive Robots," Robotics and Autonomous Systems, 42 (2003), Elsevier Science B.V., pp. 143-166.

12. Anom., V/STOL Aircraft and Propulsion Concepts; http://vertipedia.vtol.org/vstol/wheel.htm.

13. Google-X Project Wing – First Generation Aircraft; https://x.company/projects/wing/.

14. Google-X Project Wing – Second Generation Aircraft; https://x.company/projects/wing/.

15. Amazon Prime Air Drone – First Generation Aircraft; https://m.youtube.com/watch?v=cRTNvWcx9Oo.

16. Amazon Prime Air Drone – Second Generation Aircraft; https://m.youtube.com/watch?v=MXo_d6tNWuY.

17. Young, L.A., "Small Autonomous Air/Sea System Concepts for Coast Guard Missions," USCG Maritime Domain Awareness Requirements, Capabilities, and Technology (MDA RCT) Forum, Santa Clara, CA, May 2, 2005.

18. Young, L.A., Aiken, E.W., and Briggs, G.A., "Smart Rotorcraft Field Assistants for Terrestrial and Planetary Science," 2004 IEEE Aerospace Conference, Big Sky, MT, March 2004.

19. Example of "Range Extender" Technology: http://www.launchpnt.com/news/news/bid/105014/LaunchPoint-Develops-High-Specific-Power-Genset-for-UAVs (website last accessed January 9, 2017).

20. Vex Robotics educational/competition website: https://www.vexrobotics.com/wiki/Games_%26_Competitions

21. Pfaender, H., DeLaurentis, D., and Mavris, D.N., "An Object Oriented Approach for Conceptual Design Exploration of UAV-Based System-of-Systems," 2nd AIAA "Unmanned Unlimited" Systems, Technologies, and Operations, AIAA-2003-6521, September 15-18, 2003, San Diego, CA.

22. Preisner, L.J., DeLaurentis, D., Mavris, D., and Schrage, D., "Application of a Technology Identification, Selection, and Evaluation Method for the Conceptual Design of a VTOL UAV," AIAA-2002-3465, AIAA 1st Technical Conference and Workshop on Unmanned Aerospace Vehicles, May 20-23, 2002, Portsmouth, VA.

23. Bellotto, N. and Hu, H., "Multisensor-Based Human Detection and Tracking for Mobile Service Robots," IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART B: CYBERNETICS, VOL. 39, NO. 1, FEBRUARY 2009.

24. Baeg, S-H, et al, "Building a Smart Home Environment for Service Robots based on RFID and Sensor Networks," International Conference on Control, Automation and Systems (ICCAS '07), 2007.

25. Ground robot package delivery: https://www.starship.xyz/; (website last accessed January 2, 2017).

26. COTS 27x13 Propeller: http://apcserve.w20.wh-2.com/v/PERFILES_WEB/PER3_27x13E.dat; (website last accessed January 3, 2017).

27. Multirotor Electric Motor: http://www.rctigermotor.com/html/2016/Power-Type_0414/309.html (website last accessed 1-11-2017)

28. Multirotor Electronic Speed Controller: http://www.rctigermotor.com/html/2013/esc_0916/86.html (website last accessed 1-11-2017)