Towards Energy-Autonomous Unmanned Aerial System: A Bionic Approach on Solar-Electric, Multi-Vehicle Aerial Platforms for Waterborne Operations

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Abstract. An alternative approach on energy-autonomous unmanned aerial systems is proposed: By a collaborative, multi-vehicle architecture, the infinite flight-concept of High-Altitude Solar-Powered Vehicles is replaced by a bionic inspired two-mode operation. Mission tasks are conducted with full functionalities by active vehicles, while the remaining inactive vehicles rest at a sleep-like phase of minimum power consumption, increasing the efficiency of energy regeneration. As an exemplary case, a solar-electric powered system of waterborne, fixed-wing vehicles is studied. Assuming a search-and-detect mission scenario, probable vehicle and system designs are investigated. Impact of seasonal and meteorological availability of solar insolation, vehicle operation scheme, sensor and datalink properties on system performance are evaluated by a multi-agent-based mission simulation. Optimization potentials, as well as learnings on system architecture, vehicle design and mission scenario are presented.

1. Introduction
In remote, uninhabitable or hazardous environments, the utilization of Unmanned Aerial Systems (UAS) enables to sense, explore and detect, while separating human beings from threats – a valuable benefit for applications in science, civil and environmental protection.

However, the operation of systems based on small or micro-sized Unmanned Aerial Vehicles (UAVs) today requires intensive human support for launch, recovery or turn-around. Due to the limited flight range of this vehicles, this in turn requires human presence close to the theatre of operation – contrary to the initially mentioned merit of UAS application. Energy-autonomous operations display an option to eliminate a conventional turn-around for refueling or battery change and thus can help to solve this operative dilemma. However, researched approaches towards energy-autonomy in UAS are limited to quasi-infinite-flight concepts. Implementations of this...
concept are characterized by large-sized wing areas, battery mass fractions and minimized structural weight, resulting in increased the gust-responsiveness. Up to the current date, unmanned prototypes following this principle faced major aero-elastic challenges - up to structural failure due to usual atmospheric turbulence [1].

In the following, an alternative approach is proposed: Without human presence on site, a continuous operation of the aerial system is realized via in-situ resource utilization. By a collaborative multi-vehicle architecture, a two-mode operation is introduced: Comparable to a wake phase, airborne mission tasks are executed by a portion of the vehicles. To increases the effectivity of energy regeneration, a sleep-like phase of minimum activity is proposed for the rest of the vehicles. A reduction in required endurance is expected, resulting in minimized energy storage mass and finally vehicle size. As illustrated in Figure 1, a homogenic system of solar/battery-electric seaplanes is proposed for the present study: Since major parts of the earth’s surface are covered by oceans, rivers and lakes, these uninhabited, for the predominant part obstacle-free areas can be used for waterborne flight operations - without any additional infrastructure. Applicable mission scenarios range from biological explorations, coastal forest fire observation to optical inspections of offshore wind farms. Considering the EU’s joint operations in the Mediterranean Sea, also manned aircraft and vessel sorties can be strengthened by such a system: Not depending on ships or land bases, continuously on-site patrolling UAVs can help to accelerate detection and tracking of small boats or rafts in distress. As a result, time to interception and recovery by manned vessels can be optimized.

2. Investigation Methodology: Multi Agent-Based Mission Simulation
Availabiliy and efficient harvest of solar insolation is fundamental for the investigation of the proposed system. To study the impact of season and meteorology, system architecture, operational pattern and vehicle design on total performance, a multi-agent-based simulation of the mission scenario is implemented in SciLab.

2.1. Modelling of the Environment
The simulation environment corresponds to a physical mission theatre. The geometric domain is defined by a geographical reference point, as well as an eastern and a northern extent. For the assumed scenario, a latitude of 33.5°N is assumed, corresponding to a theatre in the Mediterranean Sea. The theatre’s surface is simplified as a flat pattern. The time domain is defined by sequential, constant timesteps. For the following preliminary studies, the boundaries enclose a square of 20 km edge length. A circumsolar radiation model, simple meteorological effects and ISA atmospheric conditions are considered.

2.1.1. Insolation: Circumsolar Radiation and Atmospheric Attenuation
For the local solar time and the geographical position of each vehicle, the sun elevation angle is estimated using a geometrical model as proposed by Gundlach J [2]. At orbital altitude, a Solar Constant of 1352 W/m² is assumed. Following the approach by Hall D W [3] to estimate the Global Horizontal Irradiation at sea level, corrections for atmospheric attenuation losses are applied. The effective Horizontal Irradiation is geometrically determined as the component perpendicular to the local horizontal plane.

2.1.2. Meteorological Effects: Overcast and Wind
To model the radiative effect of overcast, a homogenous cloud coverage across the mission environment is assumed. The coverage ratio is variable in time and can range from 0% (clear sky) up to 100% (fully clouded). Due to the strictly localized impact, the radiative effect is neglected for coverage ratios below 20%. The median Irradiation loss compared to clear sky conditions is determined using experimental data [4]. The diffusive lighting fraction is assumed to be proportional to the cloud coverage ratio. Wind is modelled as a constant vector field across the mission environment.
environment defined by a scalar windspeed and normalized directional vector. Both can be defined independently for each timestep. Local sea surface drafts and wave transport phenomena are not considered in this study.

2.2. Agents: Vehicles and Search Target
The vehicle agents operate autonomously within the mission environment, according to movement and interaction rules. The status of vehicle properties, including current position, groundspeed, airspeed, battery status, as well as sensor detections and datalink connection effect the application of these rules.

2.2.1. Vehicle Movement and Interaction Rules
For initialization, a total vehicle number and a fixed number of vehicles in parallel flight operation is defined. The flight path of active vehicles is governed by a flight pattern or algorithm. The mission environment’s surface is scanned for search targets along the flight trajectory. If a minimum charge status of 20% is encountered, the active status is transferred to an inactive vehicle within minimum distance featuring a charge status of at least 80%. If no inactive vehicle is in sufficient recharging state, the number of active vehicles is temporarily reduced, until the required charge status is obtained. In case of the current windspeed exceeding the maximum horizontal airspeed, flight operations are discontinued until windspeed decreases. The vehicles generally operate at the speed of best range $V^*$, unless the resulting groundspeed is below $0.1 \cdot V^*$. A correction for windspeed is applied, so that the groundspeed vector follows the direction governed by the flight pattern. If the target object is within the projection of the sensor plane, the active vehicle broadcasts the information via radio link. All vehicles (active and inactive) within range receive the information and forward it.

2.2.2. Vehicle Properties: Energy Balance, Sensor Field of View and Datalink Range
Each $i^{th}$ vehicle’s energy balance is determined at the end of the $j^{th}$ timestep (with duration $\Delta t$), evaluated by the following equation:

$$E_{\text{Batt},i}(t_j) = E_{\text{Batt},i}(t_{j-1}) + P_{\text{harvested},i}(t_j) \cdot \Delta t - P_{\text{consumed},i}(t_j) \cdot \Delta t$$

(1)

Solar Irradiation Harvest
The effective harvested energy is dependent on the net PV array area $S_{\text{PV,Cell}}$, the PV array efficiency $\eta_{\text{PV,Array}}$ and the charging efficiency $\eta_{\text{ChargeSys}}$:

$$P_{\text{harvested},i}(t_j) = P_{\text{irradiation, horizontal}}(t_j) \cdot S_{\text{PV,Array}} \cdot \eta_{\text{PV,Array}} \cdot \eta_{\text{ChargeSys}}$$

(2)

The array efficiency $\eta_{\text{PV,Array}}$ is modelled in correlation with PV Cell Temperature and the diffusive fraction of the current lighting condition. Correlations for thin film solar cells are retrieved from experimental data. A simple, empirical model for PV cell thermal balance is used, depending on ambient temperature and windspeed [6]. A characteristic charging efficiency $\eta_{\text{ChargeSys}}$ for electric vehicles of 0.85 is assumed.

Vehicle Power consumption
Depending on the vehicle status (active/inactive), the power consumption is described as following:

$$P_{\text{consumed},i}(t_j) = P_{\text{propulsive},i}(t_j) + P_{\text{system},i}(t_j) + P_{\text{comm},i}(t_j)$$

(3)

For flying vehicles, the propulsive power $P_{\text{propulsive},i}$ is determined in correlation to the aerodynamic drag $D_{\text{aero}}$ and propulsive efficiency:

$$P_{\text{propulsive},i}(t_j) = D_{\text{aero}} \left(V(t_j)\right) \cdot V(t_j) \cdot \frac{1}{\eta_{\text{propulsive}}(V(t_j))}$$

(4)

A Quadratic Drag Polar considering parasitic and induced contributions is used [7]:

$$C_D = C_{D0} + \frac{C_L^2}{\pi \alpha}$$

(5)

The Zero-Lift-Drag Coefficient $C_{D0}$ is estimated by a method presented by S H Chicken [8]. Empirical information on Skin Friction Drag is taken from [9]. A typical Span Efficiency Factor $\epsilon$ of 0.75 is
assumed [7]. To model propulsive efficiency, contributions of propeller, motor and speed controller are considered. The optimum propulsive efficiency is assumed to match the airspeed of maximum Lift-to-Drag Ratio $V^*$. Assumptions for realistic component efficiencies are obtained from [10]. An exemplary energy balance over 24 hours for a system of 27 vehicles is given in Figure 2:

![Figure 2. Harvestable Power and Charge Status for a System of 27 Vehicles for 24h Operation](image)

Sensor Field of View and Area Coverage
In correlation with the flight altitude of active vehicles and the field of view (FOV) of the assumed micro bolometer sensor, the covered area on the mission map is determined by a simple projection approach, as shown in Figure 3 [11]. The resulting image resolution in sensor pixel per meter is used to apply optical detection criteria. The area cumulatively scanned by the sensor is used to derive total coverage and hourly coverage rate.

Datalink Range
A basic free space loss model is used to determine the maximum datalink range. It is assumed that no antenna tracking is implemented, and thus simple dipole antenna characteristics apply. Transmitting power and receiver sensitivity levels from available systems are assumed. For the present modelling, a datalink connection between two vehicles is established, if the distance between the positions of the vehicles is smaller than the maximum radio range.

2.2.3. Target Object
The target object is modelled to resemble a small boat or raft. A significant length of 3.5m is assumed, describing either the diameter of a raft or the deck width of a small boat. The object to detect has no means of propulsion or navigation. Appearing at a certain timestep at an initial position, windspeed induced drift governs the movement of this agent. Empirical estimation equations are used to determine the leeway speed [11].

3. Parameter Studies
In this section, the performance sensitivity of the multi-vehicle system to availability of solar irradiation and system architecture parameters is investigated.
3.1. Vehicle Design
For this initial study, the vehicle design purposely follows a non-optimized rationale: Data on operational manned and unmanned waterborne airplanes, as well as proven literature methods are utilized to derive characteristic vehicle geometry- and mass trends. For energy generation, conformal, thin-film PV cells [14] are assumed to be integrated into the upper wing skin. An effective cell surface of 80.00% of the wing reference area is estimated. Experimentally proven components are taken from literature and complemented with manufacturer data for total payload mass estimation [15],[16]. The payload fraction is varied in five steps between 2.50% to 25.00%, resulting in Take-Off Weights (TOW) between 0.70 kg and 7.04 kg. The effective battery mass is determined by subtracting a seaplane-typical empty mass fraction and applying corrections for installation and charging management electronics. The resulting battery capacity is estimated using data on proven cell types. As a key figure, the ratio between endurance at the speed of best range (as presented in 2.2.2.), and idealized charging time (for a constant irradiation of 1000W/m²) are determined. A trade-study, illustrated in Figure 4, between minimizing recharging time and maximizing vehicle range is conducted. An increase in specific energy harvest is observed for minimized vehicle mass. With the harvested power being proportional to the wing’s reference area $S_{Ref}$ (correlating to the square of a significant length $L^2$) and the vehicles mass being proportional to $L^3$, this correlation follows basic physical scaling laws. However, with decreasing size, the impact of manufacturing inaccuracies, as well as low Reynolds Number regimes deteriorate the aerodynamic efficiency. As the speed of best range, as well as the battery mass fraction decrease for lighter configurations, range performance is further degraded. For a balanced initial design point, a configuration with a payload fraction of 7.50% TOW is selected, as shown in detail in Figure 5.

![Figure 4. Trade-Off Plot for a variation of TOW](image)

![Figure 5. Mass Breakdown for Design Point](image)

3.2. Vehicle Flight Pattern
As a proven concept, the Search and Rescue Manual of the U.S. Coast Guard proposes a ladder-pattern for effective areal detection missions [11]. In the present implementation, the distance between two long legs is assumed to correspond to one half of the sensor FOV. As an alternative, a potential field-model based algorithm is considered. The resulting non-deterministic movement pattern is commonly implemented for robotic swarms, but recently also proposed for UAS operations [13]. Each actively flying vehicle is assumed to display a virtual potential source. Additionally, the positions of the previous timesteps are defined as a potential source (reduced in strength), so that the vehicles are consequently moving away from areas already covered. To study the effectivity of both approaches, the following experimental setup is assumed: For each flight pattern, ten reference missions of 24h duration are simulated. The starting time is set to 05.00 am on the 172nd calendar day. For every case, one single target object is randomly placed on the mission map. The time until the first vehicle detects the target is regarded, as well as the total area coverage within the 24h. For both patterns, the vehicle system consists of 36 vehicles in total, with two vehicles being airborne in parallel. Due to the deterministic character of the ladder-pattern, complete area coverage is achieved - except for numerical inaccuracies in the order of 1‰. For the potential-field based algorithm, the average area
coverage accounts to 95.5% within the first 24h. Although the fastest detection can be found for the non-deterministic algorithm, also the most enduring timespans until first detection are found. For the assumed mission scenario, an increased reliability of the ladder pattern in terms of area coverage, as well as detection time is of significant benefit.

Figure 6. Ladder-Pattern Movement Scheme

Figure 7. Non-Deterministic Movement Pattern

Figure 8. Time to Detection for Ladder Pattern

Figure 9. Time to Detection for Non-Deterministic Movement Pattern

3.3. Impact of Circumsolar Radiation and Overcast on System Energy Balance

The extreme cases of solar irradiation in summer- and winter solstice conditions are regarded, both for clear sky and overcast conditions. With a fixed total number of 66 vehicles, the number of flying vehicles is iterated until the total systems energy balance converges within 5‰. A fixed flight operation level of 507m above ground is regarded.

Table 1. Impact of Irradiation Condition on System Activity

| Cloud Coverage | Summer Solstice | Winter Solstice |
|----------------|-----------------|-----------------|
|                | Clear Sky       | 90-100 % Overcast | Clear Sky | 90-100 % Overcast |
| Total Vehicle Number | 66               | 66              | 66       | 66               |
| Active (Flying) Vehicles | 4               | 2               | (1)*     | 2               |

* limited to two consecutive days of overcast

As given in Table 1, the maximum system activity can be observed for a summer day with clear sky conditions. The resulting recharging energy per day exceeds the battery capacity of a single vehicle by a factor of 3.36. For the same positioning of the sun but overcast conditions, the daily harvested energy is reduced to less than a third. The number of active vehicle ratio is decreased by 50%. On a clear sky
winter day, comparable insolation conditions are found. For a continuous overcast on winter solstice, flight operation is reduced to one single vehicle at a time. This system state can be sustained for two consecutive days of overcast conditions.

3.4. Variation of Flight Altitude
Vehicle flight altitude has a significant impact on sensor area coverage and the detectability of objects. Power consumption for climb and potential energy increment also affect the battery balance of each vehicle. Three flight operation altitude levels are defined, following an experimentally proven criterion for detection with miniature bolometer sensors [15]: For the target object’s significant dimension and the assumed sensor resolution, the maximum altitude for reliable detection is determined to 1015m above ground. Additionally, 507m and 254m are regarded. A target object is placed in the geometric center of the mission area. The number of active vehicles flying in parallel is determined for the accumulated width of the projected sensor planes (see Figure 3) being constant. The total number of vehicles is iterated for a balanced total energy of all vehicles in the investigated condition. To quantify the efficiency of the systems, an effective area performance regarding the total number of vehicles is introduced. A comparison of this measuring unit for the resulting six configurations is given in Figure 10, exhibiting a performance decline for decreased flight altitude. For system energy equilibrium, the number of inactive vehicles raises, as the number of active vehicles is increased. As a result, a lowered flight altitude and thus reduced climb energy is no valid trade against the steady flight consumption of additional active vehicles required to scan the same area.

3.5. Datalink Architecture
For the present mission scenario, an effective communication of location and drift of the search target is crucial. With the modelling presented in 2.2.2., two alternative architectures are compared based on information on commercially available systems. In an initial approach, a prevalent 2.4 GHz based radio link is investigated. An air-to-surface relay pattern is assumed to connect active and inactive vehicles. For the resulting radio range and number of airborne vehicles, no gapless relay network can be established for the present study cases. For locations with no relay coverage, the information is consequently transported physically by flying vehicles, resulting in poor broadcasting performance, as illustrated in Figure 11. A long-range direct link architecture can display an alternative: A decade of range increase is found for 868 MHz transceiver systems, due to reduced free space losses at the expense of lower data rates. However, the information of detection is transferred instantly beyond the boundaries of the studied simulation environment.

4. Conclusion
An energy-autonomous system of multiple waterborne, photo-voltaic powered aerial vehicles for a search- and detection scenario is proposed. By utilizing a multi-agent simulation, impacts of vehicle design, system architecture and operation parameters, as well as seasonal and daily availability of solar
irradiation on total system performance and efficiency are studied. An improvement of energy harvesting and a reduction of charging time for minimized vehicle size and mass is observed. Regarding aerodynamic performance, endurance, as well as range, a compromise towards increased TOWs can be of interest. As the vehicle sizing parameters are initially chosen for workable waterborne design, potentials for aircraft optimization are not exhausted yet. Considering the non-utilized energy surplus in clear sky conditions in summer and shortages for overcast conditions in winter indicate potentials for advanced energy storage and management concepts. Assuming a fixed total number of vehicles, varying the number of vehicles flying in parallel is observed to be the most effective parameter to match total system consumption with available irradiation. A variation of flight altitude has minor impact regarding target search efficiency, though, it can serve as potential energy storage. Communication link range has proven to be critical for effective data transmission. Long-range transceiver systems are required with minimum system mass and receiving consumption. Considering the required number of vehicles and the ratios of inactivity found, cost-intensive sensor payloads might be eliminated by economic aspects. Following the promising results from 3.3., a long-term study is required to assess an all-year operability. Subsequent to this study, also effects of swarm hybridization on system architecture and performance should be studied: Surface vehicle based satellite-link relays display a promising enhancement for remote mission theatres.

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