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THESIS

**ENERGY CAPTURE MODULE (ECM) FOR USE IN
UNMANNED MOBILE VEHICLES (UMVS) WITH A
SPECIFIC STUDY OF THE DRAGANFLYER X6 UAV**

by

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September 2010

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VEHICLES (UMVS) WITH A SPECIFIC STUDY OF THE DRAGANFLYER X6
UAV**

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ABSTRACT

Unmanned drones, robots, and vehicles are often chosen to perform tasks in harsh and dangerous environments. Autonomous vehicles are ideal in tactical situations when these vehicles can perform functions for warfighters when the risk to human life is significantly too high. In particular, unmanned aerial vehicles (UAVs) have become a common staple of military operations. Common sizes range from slingshot-launched spy bots to global guardians.

Small UAV of all types have limited mission endurance due to volume and weight constraints of their energy storage and power sources. In many cases, UAVs are limited in the extent to which they could provide tactical advantage because of their need to be recharged or refueled. Even with the use of highly efficient energy and power sources, it is extremely difficult to design a feasible energy system that will provide power for prolonged duration missions. A method, energy capture, exists to provide recharging of an energy source remotely. By utilizing electromagnetic waves, energy can be transmitted wirelessly over great distances. This method has been implemented in several forms today, and shows promise as a possible way to provide for much greater UAV mission endurance.

An Energy Control Module (ECM) is proposed as a scalable and Modular Open System (MOS) design concept that can utilize either a tuned laser photovoltaic cell or a microwave receiver to convert received electromagnetic energy to maintain the onboard UAV platform battery charged. The ECM can utilize ground or shipboard based power supply to wirelessly transmit power to a UAV.

This thesis presents a study of the characteristics needed for an ECM that allows a small UAV platform to remain on station and perform its designed functions while recharging its energy source for prolonged duration missions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
DoD	Department of Defense
DRM	Design Reference Mission
DX6	Draganflyer X6 (UAV)
ECM	Energy Capture Module
ESD	External Systems Diagram
FFBD	Function Flow Block Diagram
GW	Ground Wave (Propagation)
IPPD	Integrated Product and Process Development
LOS	Line of Sight (Propagation)
MET	Mission Effective Time
OV1	Operational View 1
POE	Projected Operating Environment
RF	Radio Frequency
SW	Sky Wave (Propagation)
TT	Transit Time
UAV	Unmanned Aerial Vehicle

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EXECUTIVE SUMMARY

Unmanned drones, robots, and vehicles are often chosen to perform tasks in harsh and dangerous environments. Autonomous vehicles are ideal in tactical situations when these vehicles can perform functions for warfighters when the risk to human life is significantly too high. In particular, unmanned aerial vehicles (UAVs) have become a common staple of military operations. Common sizes range from slingshot-launched spy bots to global guardians.

Small UAV of all types have limited mission endurance due to volume and weight constraints of their energy storage and power sources. In many cases, UAVs are limited in the extent to which they could provide tactical advantage because of their need to be recharged or refueled. Even with the use of highly efficient energy and power sources, it is extremely difficult to design a feasible energy system that will provide power for prolonged duration missions. A method, energy capture, exists to provide recharging of an energy source remotely. By utilizing electromagnetic waves, energy can be transmitted wirelessly over great distances. This method has been implemented in several forms today, and shows promise as a possible way to provide for much greater UAV mission endurance.

This thesis presents a study of the characteristics needed for an Energy Capture Module (ECM) that allows a small UAV platform to remain on station and perform its designed functions while recharging its energy source for prolonged duration missions. An ECM, **Figure 1**, is proposed as a scalable and Modular Open System (MOS) design concept that utilizes both photovoltaic and radio frequency (RF) energy to recharge a small UAV without the need of retrieval for refueling.

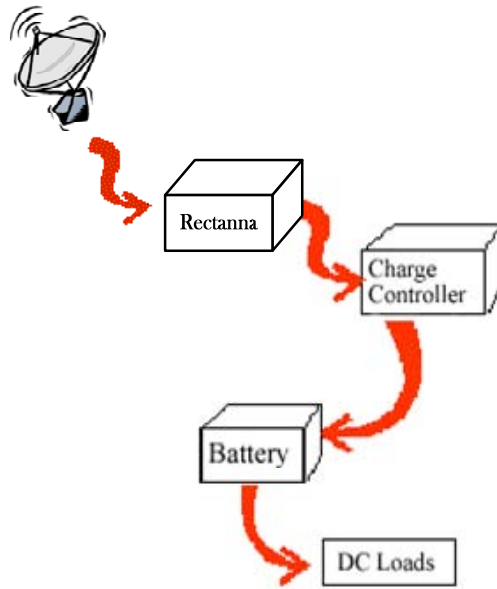


Figure 1. Energy Capture Module (ECM) Concept of Operation

Referring to Figure 1, energy is provided to the UAV for battery charging through transmission of power from a radiating antenna on the ground, or possibly from another unmanned aerial platform, to a rectenna unit on the UAV. A rectenna is a rectifying antenna that directly converts electromagnetic radiation to a direct current (DC) voltage. The captured energy provides maintains the UAV operational indefinitely as long as sufficient energy is transmitted.

To demonstrate the feasibility of the technology, an ECM is then designed for use in an existing small UAV, the *Draganflyer X6* (DX6), **Figure 2**. The DX6 is a remotely operated, UAV, miniature helicopter designed to carry wireless video and still cameras. The DX6 uses a unique 6-rotor design that provides energy efficient hovering capabilities.

Its collapsible, carbon-fiber design provides durability and portability for numerous military applications. However, the current flight time is limited to approximately 20 minutes. This thesis provides a design for an ECM that fits in the existing vehicle volume and weight constraints in order to provide unlimited mission endurance within the range of the energy capture method.



Figure 2. Draganflyer X6

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I. INTRODUCTION

A. BACKGROUND

Section 220 of the FY2001 defense authorization act (H.R. 4205/P.L. 106-398 of October 30, 2000) calls for the armed forces to field unmanned, remotely controlled technology. The Department of the Navy (DON) master plans calls for acquiring Unmanned Aerial Vehicles (UAVs) for three primary mission areas: (1) long-dwell, standoff Intelligence, Surveillance, and Reconnaissance (ISR) operations; (2) penetrating surveillance/suppression of enemy air defense (SEAD)/strike operations; and (3) tactical surveillance and targeting operations.

UAVs like the MQ-1 Predator are considered long range and high endurance vehicles. With an operating range in excess of 800km and a operational range of over 24 hours, the MQ-1 is capable of fulfilling most of the aforementioned master plan capabilities; however, the MQ-1 is limited by fuel and incapable of providing long-term surveillance without refueling. UAVs like the WASP III are tactical vehicles with reduced range and endurance. These UAVs are typically hand launched and light weight for field use.

B. UAV MISSION CAPABILITY AND METRICS

Currently, small UAVs have a very limited operational range. For UAVs, operational range is a function of energy storage capacity, flight time to the mission area (Transit Time (TT)), and payload (mission equipment), and on station time (Mission Effective Time (MET)). The MET is also known as the “*time window*” on target, is displayed in **Figure 3**. Operational range is represented as a function of time by **Equation 1**:

$$\text{Operational range (time reference)} = f(t) = TT_{\text{deploy}} + MET + TT_{\text{return}} \quad (1)$$

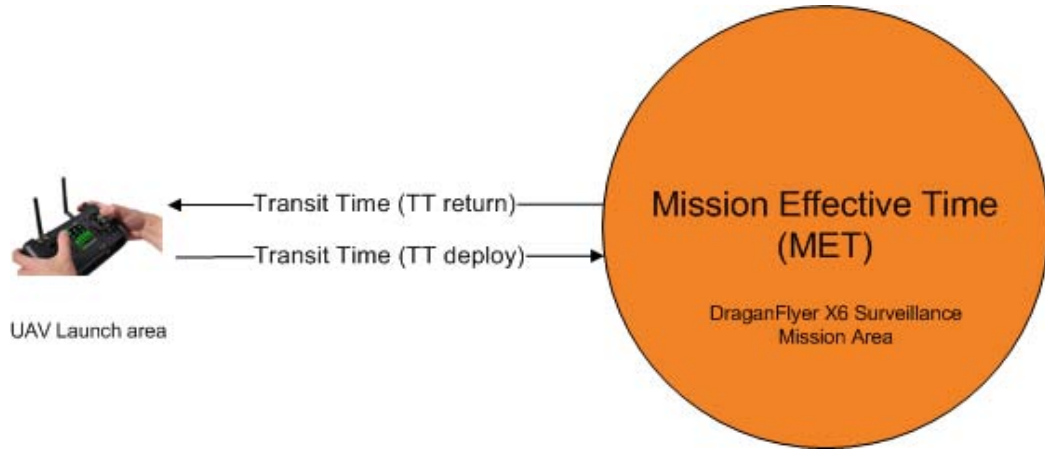


Figure 3. Time Window on Target (Mission Effective Time)

Mission Effective Time (MET) is a term used to describe the actual time an instrument (UAV) is considered to be on station performing desired function(s). The time/distance ($TT_{\text{deploy/return}}$) an instrument is required to fly to be on mission is not included in the MET. For most tactical UAV, the MET is limited to a small number of minutes.

C. PROBLEM STATEMENT

In many cases, tactical UAVs are limited in the extent in which they can provide a tactical advantage because of their need to be recharged or refueled. Even with the use of highly efficient energy sources, it is extremely difficult to design a feasible energy system that will provide power for prolonged tactical UAV missions. ***A system is needed to provide a means to maintain a small tactical UAV platform operational indefinitely.***

A solution is needed to extend MET for a small UAV platform in order to maintain operations (in flight) without the need to be extracted for refueling. Energy capture is a technology that would utilize wireless power transmission to maintain a UAV operational indefinitely. By using ground-based directional array of microwave antennas, microwave energy, along with communication and navigational commands, power can be beamed directly to the UAV. A portion of the energy beam would be rectified and used for battery charging. The other portion of the energy beam would be filtered and the

amplitude reduced for navigational and communication commands. Since microwave power transmission has an efficiency levels exceeding 85% (antenna to antenna), the UAV could remain on station indefinitely.

D. THESIS OUTLINE

This section provides succinct overviews of each chapter within this thesis. The scope of the thesis is limited to a feasibility study for an ECM concept that could be implemented on a specific existing UAV platform.

1. Chapter II: Mission Context and Concept Alternatives

This chapter describes the mission context, and defines the problem that this thesis addresses. This chapter will also discuss alternative energy solutions, described within the Concept Alternatives.

2. Chapter III: Platform Implementation

This chapter discusses the Energy Capture Module specific to the Draganflyer X6 platform.

3. Chapter IV: Energy Capture Module (ECM) Design

This chapter provides the Operational View (OV-1), the External Systems Diagram, and the Functional Architecture created from the Mission Context. Chapter IV then decomposes each level of the Functional Architecture. The architecture provided in this chapter provides the basis for the solution to the capability gap identified in the Mission Context.

4. Chapter V: Summary and Conclusions

This final chapter provides a summary and conclusion to the thesis. It summarizes the need for the proposed system, the concept of the proposed system, and the benefits of creating this system.

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II. MISSION CONTEXT AND CONCEPT ALTERNATIVES

This chapter describes the mission context, and defines the problem that this thesis addresses. This chapter discusses alternative energy solutions, described within the Concept Alternatives section.

A. PROBLEM BACKGROUND AND DEFINITION

Many technological advances have been made in the field of unmanned vehicles; particularly, in Unmanned Aerial Vehicles (UAV) field. Regardless of the specific platform of discussion, energy is always a significant limiting factor to the system/platform performance.

Since the turn of the 21st century, information has arguably become the key to successfully fighting a war, planning a mission, or executing an operation. Surveillance systems have proven to fulfill the capability to provide real-time intelligence; however, it is extremely difficult to place a camera in a specified location on demand and keep that camera on station for an extended period of time. Fixed position cameras can only partially provide intelligence within the field of view of the camera; assuming the camera's presence is not known.

B. MISSION CONTEXT

The mission context explains the expectations and requirements that the desired system must meet from an operational perspective. Specifically, the mission context focuses on:

- How the system will be used
- What the environmental and operating conditions surrounding the system

1. Problem Definition

UAVs are capable of providing passive surveillance with the limitation of energy. In the time required to remove an UAV from a prime position, recharge or refuel, and

return it on station, vital information has been potentially lost. A system is needed to provide a means to maintain a tactical UAV platform operational indefinitely.

2. Operational Need

For the context of this thesis, a capability is needed to provide a network of for mobile surveillance over a target area to increase security and intelligence. Capabilities include:

- Real time surveillance
- Remotely operated
- Centrally monitored and controlled
- Each unit is capable of remaining operational indefinitely without the need of recharging

3. Metrics

The primary metric is measured by performance of a proposed system to extend the flight duration, the Mission Effective Time (MET) of battery powered UAVs to an indefinite period. The metric used for this thesis is specifically confined to *extending the operational time (MET) of a tactical UAV*.

C. CONCEPT ALTERNATIVES

Concept selection is process by which various solutions are formulated and compared against the need statement. The purpose is to “*refine*” or narrow the spectrum of materiel solutions (Blanchard & Fabrycky, 2006). The solution that is most feasible and likely to achieve the desired system objectives and meet system requirements typically becomes the chosen system design. There are numerous alternative solutions. For the purpose of this thesis, the following concepts are considered:

- Hydrogen Fuel Cells
- Solar Energy Cells
- High Capacity Batteries
- Radioisotope Thermoelectric Energy
- Energy Capture

Hydrogen Fuel Cells

Hydrogen fuel is considered one of the most promising energy sources that are currently under development. Hydrogen fuel cells, like generators and other engines, are energy conversion devices; meaning they convert stored energy within a fuel into usable energy. The Hydrogen energy extraction process uses an electrochemical reaction to extract energy directly in the form of heat and electricity. Despite being a promising technology, hydrogen fuel cells would require refueling and ultimately not meet mission requirements.

Advantages of Hydrogen fuels cells:

- Excellent Reliability and maintenance—no moving parts
- Very low noise emissions—no moving parts

Disadvantages of Hydrogen fuel cells:

- Weight—requires relatively heavy conversion support equipment
- Size—conversion support equipment requires excessive space
- Would require refueling—cannot support operational need

Solar Energy Cells

Solar energy is a renewable energy source that converts the sun's radiation by means of a photovoltaic process. Outside of the atmosphere, the sun can provide approximately 1,300 watts per square meter. At the earth's surface, the power density drops off to approximately 1000 watts per square meter. For the limited size of most tactical UAVs, it is clear that solar cells would not provide sufficient energy to meet mission requirements. Although it is clear that solar energy cannot meet the stakeholder's power need, it is capable of meeting the weight requirement.

Advantages of Solar energy cells:

- Solar cells make no noise while collecting and converting energy.
- Lightweight
- Virtually maintenance free – no moving parts
- Utilizes a free and renewable energy source

Disadvantages of Solar Energy cells:

- Size—because cells require relatively large amounts of space to collect adequate energy
- Limited use—Can only be useful when sunlight is present

High Capacity Batteries

Lithium polymer batteries have evolved from lithium-ion batteries. The primary difference is that the lithium-salt electrolyte is not held in an organic solvent, but rather in a solid polymer composite such as polyethylene oxide. The advantages of Li-ion polymer over the lithium-ion design include potentially lower cost of manufacture, adaptability to a wide variety of packaging shapes, and ruggedness.

A key factor against higher capacity batteries is the fact that eventually they would need to be recharged, thus not meeting the stakeholder's needs and not capable of fulfilling the desired mission capability.

Advantages of High Capacity Batteries cells:

- Virtually maintenance free—no moving parts
- Rechargeable

Disadvantages of High Capacity Batteries cells:

- Size—higher capacity batteries are proportionately larger
- Higher capacity cells are also proportionately heavier
- Would eventually require recharging

Radioisotope Thermoelectric Energy

Radioisotope Thermoelectric Generators (RTGs) use isotopic radioactive decay as a means of energy. This process utilizes thermoelectric couples or "thermocouples" to convert heat from the radioactive material into electricity. As an unstable atomic nucleus spontaneously loses energy (decays) it emits ionizing particles and radiation. The ionizing particles interact with the surrounding material and generate heat. This generated heat is converted into electrical energy by way of the thermocouples.

The RTG would require heavy shielding to ensure personnel exposure so that limits would not be exceeded.

Advantages of Radioisotope Thermoelectric Energy cells:

- Virtually maintenance free—no moving parts
- Long life cycles
- Relatively high power densities

Disadvantages of Radioisotope Thermoelectric Energy cells:

- Weight—requires heavy shielding for personnel safety
- Political ramifications—because RTGs can be converted to be used as a “dirty bomb”

Wireless Power Transmission (Energy Capture)

Wireless power transmission (Energy beaming) has the potential to meet the stakeholder’s need, based on the concept that the heavier and larger components (beaming antenna and high power transmitter) of the overall system can be land based. The light weight components (rectennas or tuned photovoltaic cells) are currently available for use and can withstand power densities ranging from 230 Watts/m² to 1,800 Watts/ m² for energy beaming or even higher (6KW/ m²) for laser beaming. To meet the minimum required 240 Watts, discussed in Chapter III, (neglecting I²R losses and calculating power at the receiving antenna) and the size limitation of .16 m² **Equation 2** was used to determine the feasibility of wireless power transmission.

$$Power - Density = \frac{Power}{area}$$

$$\frac{240Watts}{.16m^2} = 750Watts / m^2$$

(2)

From an efficiency perspective, wireless transmission (whether it is for information or energy) is by far the least efficient (transmitter to receiver) means of transmission. This does not constitute wireless transmission as useless or wasteful. In many cases, the *convenience factor* overrides the efficiency factor mainly because of the significant advantages associated with wireless transmission. Low efficiencies can be ignored in cases of low energy level transmissions.

Power ratio becomes important in cases when engineers are particularly concerned with system efficiencies; especially with matters of power transmission. Power ratio can be defined simply as the power input divided by the power output of an associated system. Power ratio is expanded for many applications, including wireless transmissions, but ultimately it provides an indication of efficiency – “*how much power is being received compared to how much power is being sent?*”

Figure 4 is an illustration of the basic wireless transmission process. Although power losses (I^2R) are significant in power transmissions, to limit the scope of this thesis, the discussion will be limited to *antennas* and *free space propagation* (Stallings, 2010).

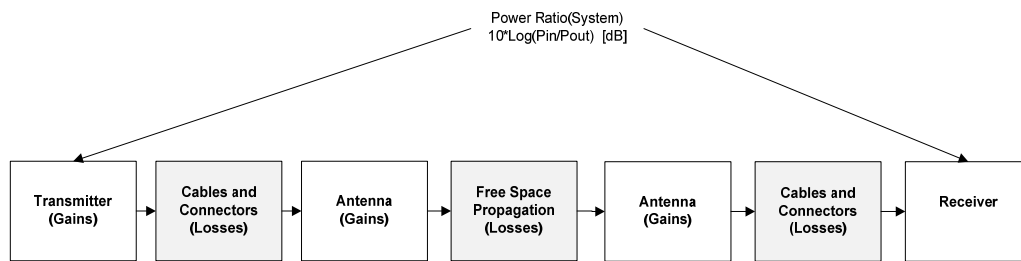


Figure 4. Power Transmission Process (Simplified)

A key component for any wireless transmission is the antenna. An antenna can be defined as an electrical conductor either for radiating electromagnetic energy or for collecting electromagnetic energy (Stallings, p. 96). A common way to characterize the performance of an antenna is by its radiation pattern. An *isotropic* antenna is an idealistic antenna that radiates energy equally in all directions. **Figure 5** is an illustration of an isotropic antenna with the antenna located at the center of the sphere. **Figure 6** illustrates basic dipole antenna (half-wave) wave pattern and **Figure 7** illustrates a parabolic reflective antenna. A parabolic reflective antenna is designed on the locus of all points equidistant from a fixed line and a fixed point not on a line (Stallings, 2010, p. 98). If the source of the electromagnetic radiation is placed at the focal point of the paraboloid, this energy bounces in parallel lines to the axis of the paraboloid; giving it a highly directional focus (Stallings, 2010).

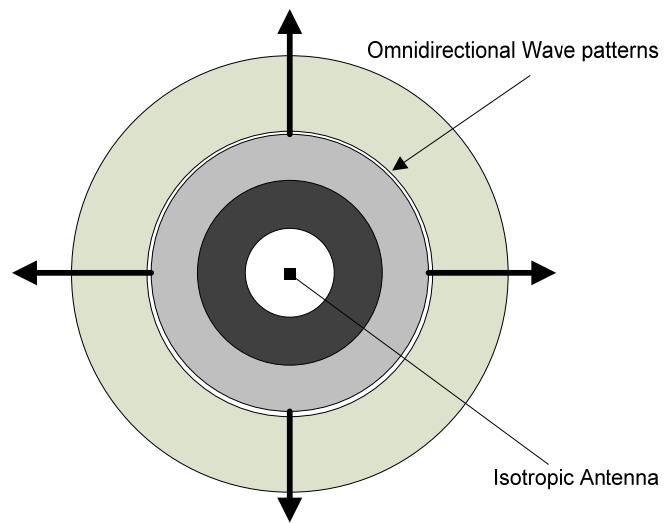


Figure 5. Isotropic Antenna Pattern

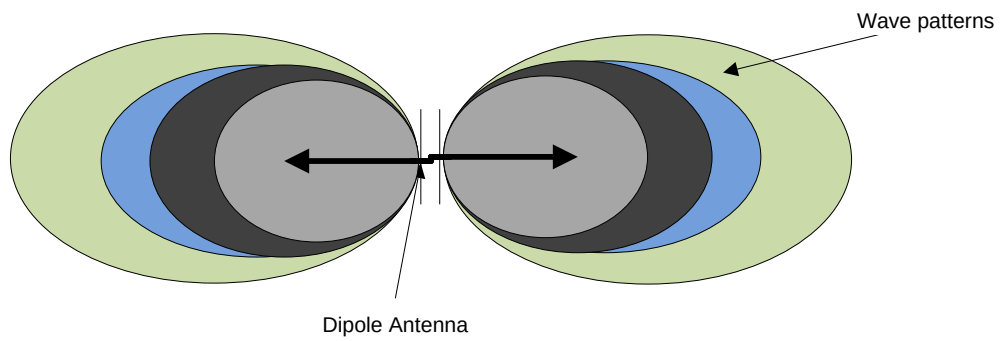


Figure 6. Directional Antenna Skewed Pattern

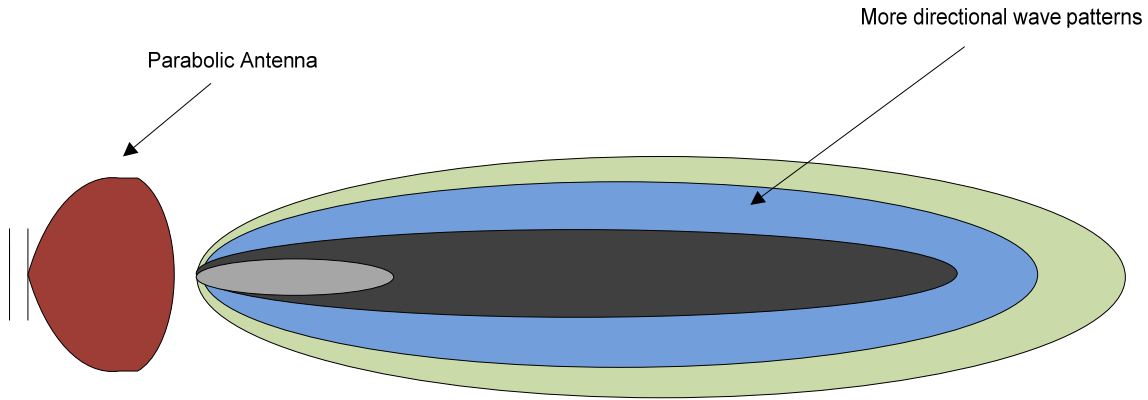


Figure 7. Parabolic Reflective Antenna Pattern

Note how the transmission pattern narrows, and range (in a particular direction) increases going from isotropic to parabolic antennas. This is the key concept in energy beaming.

As shown in **Figures 5, 6, and 7**, the shape and design of an antenna directly affects the performance and output characteristics of the antenna. An additional key concept is that antennas do not add *power* to the system; antennas merely direct the energy in a particular direction or collect the energy from a particular direction.

Gain (G) is a measure of power output, in a particular direction, compared to that produced in any direction by an isotropic (omnidirectional) antenna. One method of calculating *gain* for antenna is by determining the antenna's effective area by using **Equation 3**:

$$G = 4\pi(A_e / \lambda^2) \quad (3)$$

where: G = antenna Gain

A_e = effective area

λ = carrier wavelength

This equation and **Figures 5, 6, and 7** indicate three key properties of antennas that will be useful in the design of a solution:

- As wavelength (λ)↓ decreases, gain (G)↑ increases (Higher frequencies are better suited for energy beaming)

- As antenna area (A_e)↑ increases, gain (G)↑ increases (Larger antennas produce higher gains)
- Parabolic reflective type antennas would be best suited for this application

Isotropic antennas would be suitable for applications of communications where “dead zones” would be undesired; however, isotropic antennas would not be suitable for energy beaming (Stallings, 2010).

A final concept to be considered for solution development is free space propagation. There are three routes that a signal travels from an antenna: ground wave (GW), sky wave (SW), and line of sight (LOS).

Ground wave (GW) propagation essentially follows the curvature of the earth surface and can propagate relatively long distances. The frequency band for most GW propagation cover Extremely Low Frequency band (30–300Hz) to the Medium Frequency Band (300–3000kHz). Wavelengths (λ) in the GW band range from 10,000km to 100m. Recall, gain (G) is inversely proportional to wavelength (λ) (Stallings, 2010).

Sky wave (SW) propagation typically bounces around between the ionosphere and the earth’s surface. The frequency band for most SW propagation overlaps the Medium Frequency band (300–3000Hz) and end at the High Medium Frequency Band (3000–30000kHz). Wavelengths (λ) in the SW band range from 1000m to 10m (Stallings, 2010).

Line of Sight (LOS) propagation is not reflected by the ionosphere or the earth’s surface. It is best for direct, point-to-point communication. The frequency band for most LOS propagation covers all the bands above the High Medium Frequency Band (3000–30000kHz). Wavelengths (λ) in the LOS band range from 10m to 330nm (visible light). Combining principles for antenna design, discussed earlier, is it evident that LOS is the best means to obtain maximum efficiency for power transmission (energy capture) (Stallings, 2010).

With an understanding of the aforementioned basic concepts, a rough estimate can be made to determine the feasibility in the proposed solution. Knowing that all transmission signals diminish over distance, it should be noted that the calculations used in this thesis are for estimating purposes. There are many factors that directly affect the propagating wave and therefore the overall performance of the system. For estimating purposes, **Equation 4** will be used to determine the feasibility of the solution:

$$P_t = P_r(d)^2 \lambda^2 \left(\frac{1}{A_R A_T} \right) \quad (4)$$

where: P_t = signal power transmission

P_r = signal power receiving

λ = carrier wavelength

d = propagation distance between antennas

A_R = Area of the Receiver

A_T = Area of the Transmitter

Note: $\lambda = (3 \times 10^8 \text{ m/sec}) / \text{frequency}$

Applying arrow analysis to the above equation yields (changing only one variable at a time):

- As $\lambda \downarrow$ (decreases) : $P_t \downarrow$ (decreases)
- As frequency $\uparrow$ (increases): $\lambda \downarrow$ (decreases) – $P_t \downarrow$

The aforementioned concepts and considerations are essential in the development of an Energy Capture Module (ECM). These concepts and others help develop the requirements for the ECM Design, discussed in Chapter IV.

III. PLATFORM IMPLEMENTATION

This chapter discusses the concept design for an ECM applied to a specific UAV platform.

A. UAV PLATFORM IMPLEMENTATION

1. Draganflyer X6 Design

The Draganflyer X6 (DX6), **Figure 8** helicopter utilizes a six-rotor design that is arranged in a three counter-rotating offset pattern. The rotors pairs are mounted at the ends of the three arms, with matched sets of counter-rotating rotor blades. The differential thrust from these three equally spaced points make the DX6 helicopter capable of quick and precise maneuvers (Draganflyer.com, 2010).



Figure 8. Draganflyer X6 (DX6) (From Draganflyer.com, 2010)

Helicopter Size

Dimensions

- Width: 91cm (36in)
- Length: 85cm (33in)

- Top Diameter: 99cm (39in)
- Height: 25.4cm (10in)
- Weight: 1000 g

Dimensions

(Without Rotors)

- Width: 55cm (22in)
- Length: 49cm (19in)
- Top Diameter: 63cm (25in)
- Height: 25.4cm (10in)

Folded Dimensions

- Width: 30cm (12in)
- Length: 68cm (27in)
- Front Diameter: 35cm (14in)
- Height: 25.4cm (10in)

Folded Dimensions

(Without Landing Gear)

- Width: 13cm (5in)
- Length: 66cm (26in)
- Front Diameter: 14cm (5.5in)
- Height: 13cm (5in)

Folded Dimensions

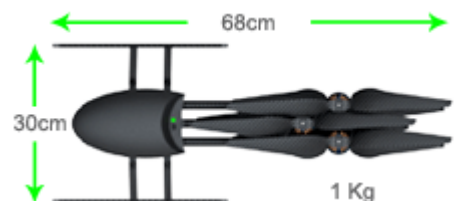
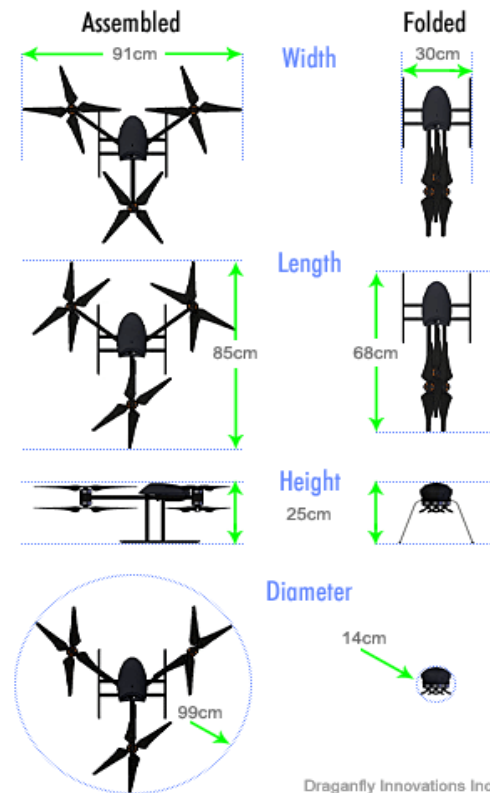
(Without Rotors or Landing Gear)

- Width: 13cm (5in)
- Length: 51cm (20in)
- Front Diameter: 14cm (5.5in)
- Height: 13cm (5in)

RF Communications

2.4 GHz Data Link

- Link Type: Helicopter to Ground & Ground to Helicopter (Two-Way)
- Controller Antenna: Omni-Directional



- RF Data Rate: 250kbps
- Receiver sensitivity: -100dBm
- Transmission Technique: DSSS (Direct Sequence Spread Spectrum)
- Frequency band: 2.4000 - 2.4835 GHz
- Data Link Channel Selection: Automatic (13 Channels)

5.8 GHz Video Link

- Link Type: Helicopter to Ground (One-Way)
- Transmitter Antenna: Omni-Directional
- Receiver Antennas: Omni-Directional & Flat Patch
- Transmission Power: 12dBm
- Transmitter Power Consumption: 500mW
- NTSC and PAL Compatible
- 7 Selectable Channels: 5740MHz, 5760MHz, 5780MHz, 5800MHz, 5820MHz, 5840MHz, 5860MHz
- Range varies with environment

Eleven (11) Onboard Sensors

- 3 Solid State MEMS (Micro-Electro-Mechanical Systems) Gyros
- 3 Solid State MEMS (Micro-Electro-Mechanical Systems) Accelerometers
- 3 Magnetometers (Magnetoresistive Sensors)
- 1 Barometric Pressure Sensor
- 1 GPS Receiver
- GPS Battery Backup: 75mAh Lithium Polymer

GPS

- GPS Used For: Position Hold, Location & Velocity Data
- Maximum Satellites Tracked Simultaneously: 16
- Position Update Rate: 4 Hz
- GPS Antenna: Ceramic Patch

Flight Characteristics

- Maximum speed: 50km/h
- Maximum wind conditions: 16kts

- Payload Capacity: 500g (DX6), 1000g (DX8)
- Peak Altitude: 8000ft (2.4km)

2. Noise

The unique rotor design maximizes thrust and minimizes sound output. This design allows the rotor blades to operate efficiently while producing less turbulence. Direct drive rotors eliminate the need for noisy gearing; further reducing its sound output. At hover, the DX6 produces less than 65dB of sound at one meter (Draganflyer, 2010).

3. Power Plant

The power plant of the DX6 provides thrust for flight and maneuvering. Power is stored in the battery, passed to the motors, converted to mechanical energy, and then turned into thrust. The DX6 is capable of carrying a 500 gram payload; this sufficient payload to carry specialized cameras systems (Draganflyer, 2010).

4. Lithium Polymer Battery

The DX6 helicopter utilizes a lithium polymer battery that has the storage capacity of 2700 mA-hrs at 14.8V. This battery stores enough energy to provide an approximate 20-minute flight (Draganflyer, 2010). The current flight duration, makes the DX6 unfeasible for military prolonged surveillance applications; however, if an Energy Capture Module was successfully integrated with the DX6, the *time window* or mission effective time (MET) could be significantly improved. This would make the DX6 an ideal platform for prolonged surveillance applications.

System Constraints

The Draganflyer's X6 (DX6) six-rotor, counter-rotating offset pattern design provides for excellent flight stability. This makes the DX6 an optimum platform for video surveillance. Coupled with high magnification surveillance cameras, the DX6 has

many military and commercial applications. Under the current configuration, the DX6 has the following characteristics:

- Range (assuming maximum flight velocity, curved flight path): 0–8km
- Power Consumption (nominal to maximum loading): 100–240W
- Operational time: 10–20 minutes
- Maximum payload: 500g

A power source is needed to provide the necessary power to extend the operational time to a more useful time. By extending the operational time of the DX6 and other Draganflyer platforms, a network of surveillance DX6s could be established to provide unprecedented capabilities in both the commercial and military sectors.

The intention is to place one or many DX6 platforms over a target area for mobile surveillance. Currently the DX6 has an operational radius of approximately 4km, compared to the 400km radius of the MQ-1 Predator. Although the MQ-1 is not a battery powered UAV, the MQ-1 is a competitor that has significant benefits, as well as drawbacks, compared to the DX6. The DX6, coupled with high magnification camera lens, could provide unprecedented surveillance capabilities. **Figure 9** illustrates the operational capabilities of DX6 compared to the MQ-1. Although the DX6 is severely limited when compared to the MQ-1, the implementation of a system that will allow for an indefinite operation flight time would significantly increase its mission capabilities.

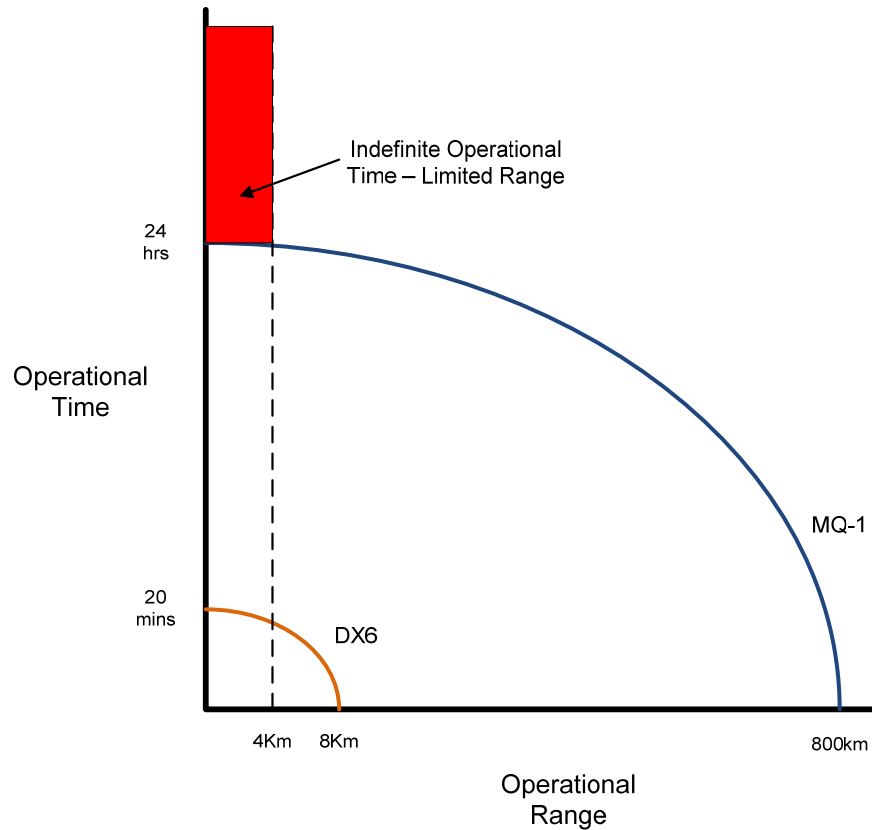


Figure 9. Draganflyer X6 vs. MQ-1 Predator Operational Comparison

B. ECM DESIGN REQUIREMENTS

To adequately meet the needs statement and successfully integrate with the DX6, *System Level* (baseline) requirements and criteria have been established. The size (S), weight (W), and distribution of weight (D) components of the baseline requirements were established based on the physical dimensions and flight characteristics of the DX6¹. The power specifications were derived from information provided by the Draganflyer Innovation Corporation (Draganfly, 2010).

The DX6 currently utilizes a 2,700 mA-Hr battery that provides approximately 20 minutes of operational flight time. High capacity batteries' storage capacity to weight ratios range from 5 to 20 mA-Hr/gram. To effectively double the operational time of the

¹ Design characteristics are based on the DX6 model. DX8 has a greater payload capacity and energy consumption.

DX6 to 40 minutes would require a storage capacity of approximately 5,000 mA-Hr. The weight of such a battery would range from 500 to 1000 grams and thus would not be a feasible solution.

Table 1 provides a summary of the energy capture for battery charging at varying wavelengths within the microwave band. The calculations were made using the following assumptions:

- Transmitter antenna size of 10 square meters (approximately 12 ft diameter dish)
- No obstructions
- A minimum of 240 Watts is required at the rectenna
- Desired beam distance is 4 km
- Frequency bands of 2.4 GHz, 35GHz, and 94 GHz are commonly used microwave bands

	2.4GHz	35GhZ	94Ghz
Power Required at Receiver (W)	240	240	240
Distance (km)	4	4	4
Receiver Area (m ²)	0.16	0.16	0.16
Transmitter Area (m ²)	100	100	100
Frequency (Hz)	2.40E+09	3.50E+10	9.40E+10
Wavelength (λ)	1.25E-01	8.57E-03	3.19E-03
Max Waveguide Power Limit	49kW	300W	39W
Power Required at Transmitter (W)	3.75E+06	1.76E+04	2.44E+03

Table 1. Power Required to beam 240 Watts to the DX6

Table 2 indicates that the higher frequencies are desirable because of the lower transmitter power required as predicted in the arrow analysis. Although providing 3 megawatts of power is achievable, it does require more support infrastructure in comparison to 2 kilowatts. This difference factor of 1000 between the 2.4GHz and 94 GHz frequencies will be presented in more detail. It should also be noted that waveguides have power limits. Power outputs over the specified limits require using a phased array antenna.

Power Specifications (P)

The DX6 operates at a battery bus voltage of 14.8V. The nominal (unloaded) power requirement for flight is 120 Watts and 240 Watts at maximum payload capacity. **Table 2** provides a summary of the estimated energy and power specifications provided by the Draganflyer Innovation Corporation.

Loading	Nominal	Maximum
Potential (Volts)	14.8	14.8
Battery Storage Capacity (mAh)	2700	2700
Time (min)	20	10
Battery Power Capacity (Wh)	40	40
Power (Watts)	120	240
Current (A)	8	16

Table 2. DX6 Power and Battery Storage Specifications

Size Specifications (S)

Based on the dimensions provided in Chapter I, the DX6 has an approximate total operating area of 30,800 cm². The central control housing, not under the blade area, occupies approximately a 200 square cm area. The unobstructed blade area is approximately 30,600 cm². In order to minimize the effects on the flight characteristics of the DX6, a 1,600 cm² area (40cm x 40cm) was chosen as the available area for the proposed solution (less than 5% of the blade area). This limitation could be exceeded or reduced through testing; however, for the purpose of this thesis, it is assumed the aforementioned limitation will have minimal impact on the flight characteristics of the DX6.

Weight Specifications (W)

The maximum payload for the DX6 is 500 grams. The DX6 would require a device that has a power-to-weight ratio ranging from 0.49 to 0.88 Watts per gram. **Table 3** and **Figure 10** provide summary and illustration respectively. It should be noted that the power required is held constant at 240 Watts, with the assumption that the camera and alternative solution will have a combined maximum payload weight of 500 grams.

Available Mission Camera Types	Power Required (Watts)	Camera (grams)	Alternative Power Source (grams)	Ratio (Watts/gram)
Micro-Board Camera (No Zoom)	240	12	488	0.492
Med Quality (No Zoom)	240	153	347	0.692
Med Quality (Zoom Capable)	240	166	334	0.719
Hi Quality (Zoom Capable)	240	227	273	0.879

Table 3. Power to Weight Ratio Tabulation

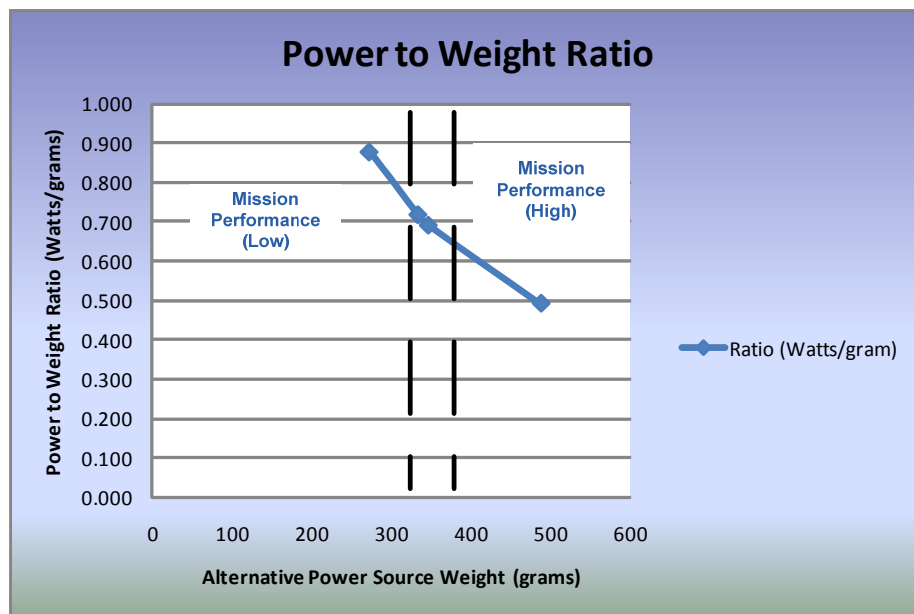


Figure 10. Power to Weight Ratio relating mission performance

Weight Distribution Specifications (D)

The DX6 rotor placement is designed to provide maximum lift at the center of gravity to provide stable flight characteristics. Any alterations to the DX6 platform must be properly aligned with the center of gravity to maintain design flight characteristics.

Table 4 provides the minimum baseline for comparison purposes. **Figure 11** provides an illustration of the *Value Hierarchy* of importance of each of the aforementioned system level requirements.

DX6 Design Component	Criteria
Size (S)	$\leq 1600 \text{ cm}^2$
Weight (W)	$< 500 \text{ grams}$
Power (P)	$\leq 240 \text{ Watts}$
Distribution of Weight (D)	Evenly distributed

Table 4. System Level DX6 Design criteria

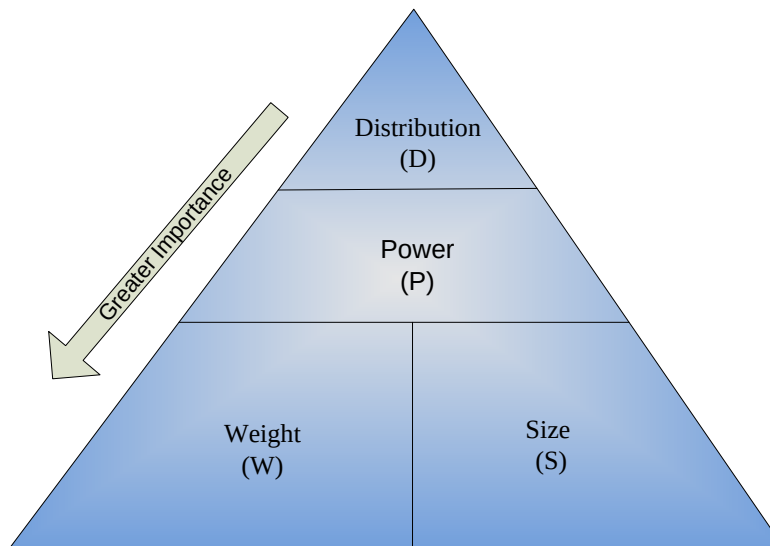


Figure 11. System Level Value Hierarchy

The aforementioned equation does not guarantee that it is possible to obtain the desired power density within the 500 gram weight limit.

Advantages of Energy Beaming/Capture for the DX6:

- Virtually maintenance free—no moving parts
- Easier to obtain a higher system reliability
- Can be used indefinitely while energy beaming is present
- Lightweight components
- Small size components (excluding antennas)
- Same communication signal used for navigational commands could be used to supply energy to charge the onboard battery (excluding the laser band)

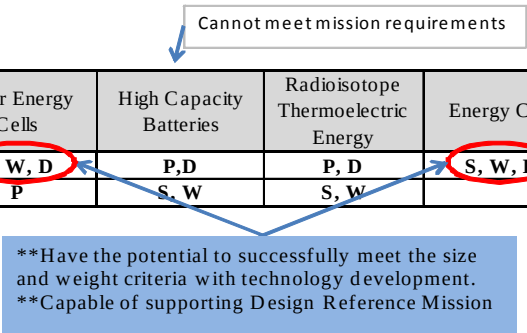
- There are two relatively experienced technology fields associated with this proposed solution: Laser and Microwave Beaming

Disadvantages of Energy Beaming for the DX6:

- High losses due to atmospheric attenuation²
- Large antennas required to maximize energy capture

Alternative Selection

None of the aforementioned alternatives had all of the key advantages to meet the baseline requirements without significant technology development. Based on the hierarchy of importance for the baseline components, solar energy and RF energy Capture were two alternatives that had a higher probability of meeting the two most important requirements, size (S) and weight (W). **Table 5** provides a summary of the results. In the comparison of the alternatives, it should be noted that a “Miss” indicates that significant technological development is needed to be considered a potential “Hit.”



Energy Source	Hydrogen Fuel Cells	Solar Energy Cells	High Capacity Batteries	Radioisotope Thermoelectric Energy	Energy Capture
DX6 Criterion Potential "Hits"	P	S, W, D	P, D	P, D	S, W, D P
DX6 Criterion Potential "Miss"	S, W, D	P	S, W	S, W	

Cannot meet mission requirements

**Have the potential to successfully meet the size and weight criteria with technology development.
**Capable of supporting Design Reference Mission

Table 5. Result Summary of Alternative Design

Solution Refinement

Because of the restricted Draganflyer X6 (DX6) specifications and the consideration of custom built components (rectannas or photovoltaic cells), quantifiable data is limited. This limitation confines the scope of this thesis so further research into the proposed solution will be necessary.

²Note: Frequencies above 10GHz become susceptible to water vapor (clouds) attenuation – this includes higher frequencies in the microwave band and all of the laser band.

Energy beaming and solar energy are prime candidates because they have the potential capability of meeting the strict size and weight limitation. Since solar energy is clearly not capable of providing sufficient energy, at present technology, the focus shifts to energy beaming. To determine the feasibility of energy beaming, some basic concepts must be considered to develop an Energy Capture Module concept model.

C. ENERGY CAPTURE MODULE (ECM) CONSIDERATIONS

The ECM combines the benefits of solar energy with the high efficiency of microwave power transmission. The same communication signal used to provide navigational signals to the DX6 will be used to recharge the DX6 battery. The ECM shall utilize a rectenna array that directly rectifies microwave signals to a DC voltage (IEEE.com).

Payload directly affects the DX6 performance. In order for the ECM to be beneficial to the DX6, a trade-off must be performed between the ECM and the mission performance. The weight between the camera equipment and the ECM must be balanced to achieve maximum performance while not exceeding 500 grams.

IV. ENERGY CAPTURE MODULE (ECM) DESIGN

A. OPERATIONAL VIEW 1 (OV1)

The Operational View 1 (OV-1) is a high-level operational concept illustration that provides a holistic description of the system under the designed operating conditions (Department of Defense, 2007). OV-1 (**Figure 12**), is derived from the Mission Context. *Note: OV1 depicts an intended application of a Draganflyer X6 (DX6). It reflects the goal of designing a system to integrate with the DX6 that will allow it to remain operational (in flight) without the need to be recharged.*

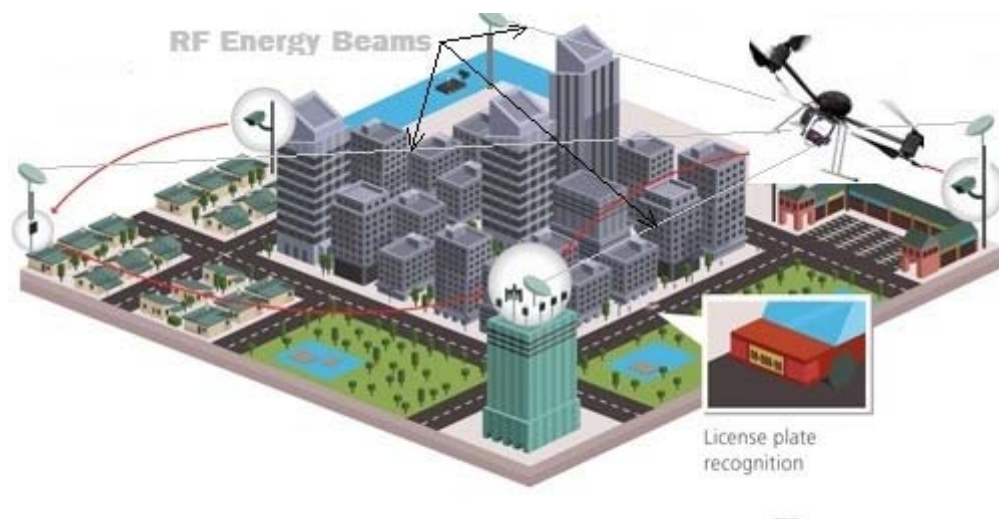


Figure 12. System Operation View (OV-1)

B. EXTERNAL SYSTEMS DIAGRAM

The External Systems Diagram (ESD) (**Figure 13**), provides a model of the system solution as it interacts with other relevant external systems. The ESD helps define the (solution) system's boundary in terms of the system's inputs and output (Buede, 2000, p. 433). The external systems were created from the Mission Context.

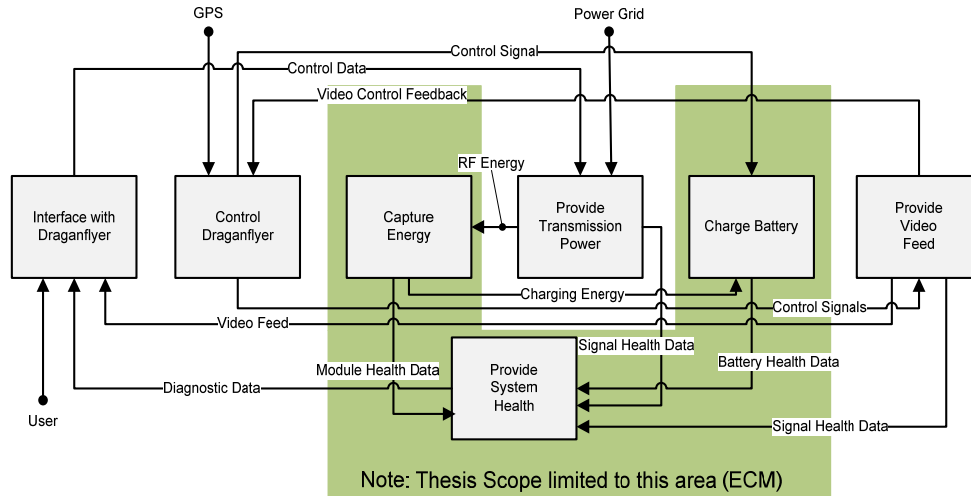


Figure 13. External Systems Diagram

C. SUBSYSTEM REQUIREMENTS

The system requirements provide the documentation on which the users and designers agree that the system shall be able to meet. For the purpose of this thesis, it is assumed that the stakeholders have agreed on the system requirements.

The subsystem requirements are generated from the Mission Context and the External System Diagram (ESD). To limit the scope of this thesis, the system requirements are confined to extending the operational flight duration of the DX6 within the operational context of the concept mission depicted in the OV-1. Further system requirements would be developed, outside the scope of this thesis, for Tower Placement, Network Communications, and Power Transmission, for instance.

ECM Requirements

A.1.0—Input/output requirements

A.1.1—Input requirements

A.1.1.1—The system shall receive Beamed Energy from power transmission towers

A.1.2—Output requirements

A.1.2.1— The system shall provide DC charging current to the DX6 battery bus.

A.1.2.2 — The system shall provide diagnostic information to the user.

A.2.0—External systems requirements

A.2.1—The system shall interface with the DX6 Battery Bus.

A.2.2—The system shall interface with DX6 control system.

A.3.0—System constraint requirements

A.3.1— The system shall comply with size and weight limitations of the DX6 platform.

A.3.2— The system shall comply with the center of gravity requirements of the DX6 platform.

A.4.0—The system requirements

A.4.1— The system shall yield a minimum of 240 Watts to maintain the DX6 in flight.

Figure 14 provides a top-level Functional Flow Block Diagram (FFBD) of the Energy Capture Module. Each block is decomposed into system level requirements.

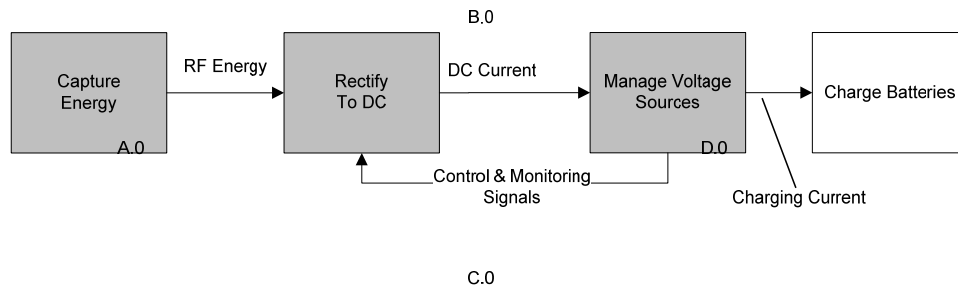


Figure 14. Top-Level FFBD

Capture Energy requirements are determined by calculating a power budget based on loading characteristics of the DX6 in flight. The DX6 has limited information regarding exact loading characteristics; however, based on the information provided, some system requirements have been derived:

A.0—Capture Energy Requirements

A.0—Component requirements

A.1.1—The *signal reception* component shall have maximum *Gain* achievable to provide a minimum of 240 Watts.

A.1.2— The *signal limiter and conditioner* component shall:

- Pass high amplitude energy signal for battery charging
- Duplicate and reduce a portion the signal to be used for Navigational commands

B.0—Rectify to DC Requirements

B.0—Component requirements

B.1—The *impedance matching* component shall have match circuit impedance to obtain maximum power transfer.

B.2.1—The *signal rectification* component shall provide *clean* DC sufficient for battery charging and compatible with the DX6 onboard battery.

B.2.2—The *signal rectification* component shall provide feedback information to the “*Manage Voltage Sources*” (D.0)

C.0—Manage Voltage Sources Requirements

C.0—Component requirements

C.1—The *manage charging source* component shall monitor energy sources to ensure proper charging and float voltage is applied to the battery bus.

C.2—The *compare battery voltage to source voltage* component shall ensure the voltage source does not act as a battery load.

D.0—Charge Batteries

D.0—For the purpose of this thesis, the Charge batteries component is self explanatory and will not be further decomposed.

D. FUNCTIONAL ANALYSIS

The purpose for performing a functional analysis is to develop the top-level system architecture to further develop system *requirements* and *structure* (Blanchard & Fabrycky, 2006, p. 78). Each sub-level, displayed in **Figure 14**, is decomposed in the subsequent **Figures 15, 16, and 17**.

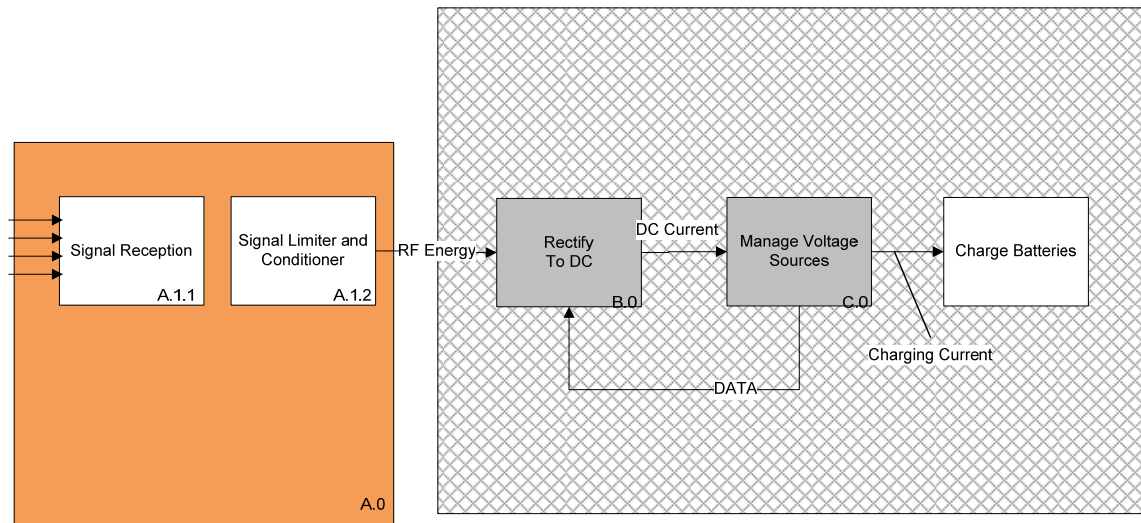


Figure 15. Capture Energy (Level 1) Decomposition

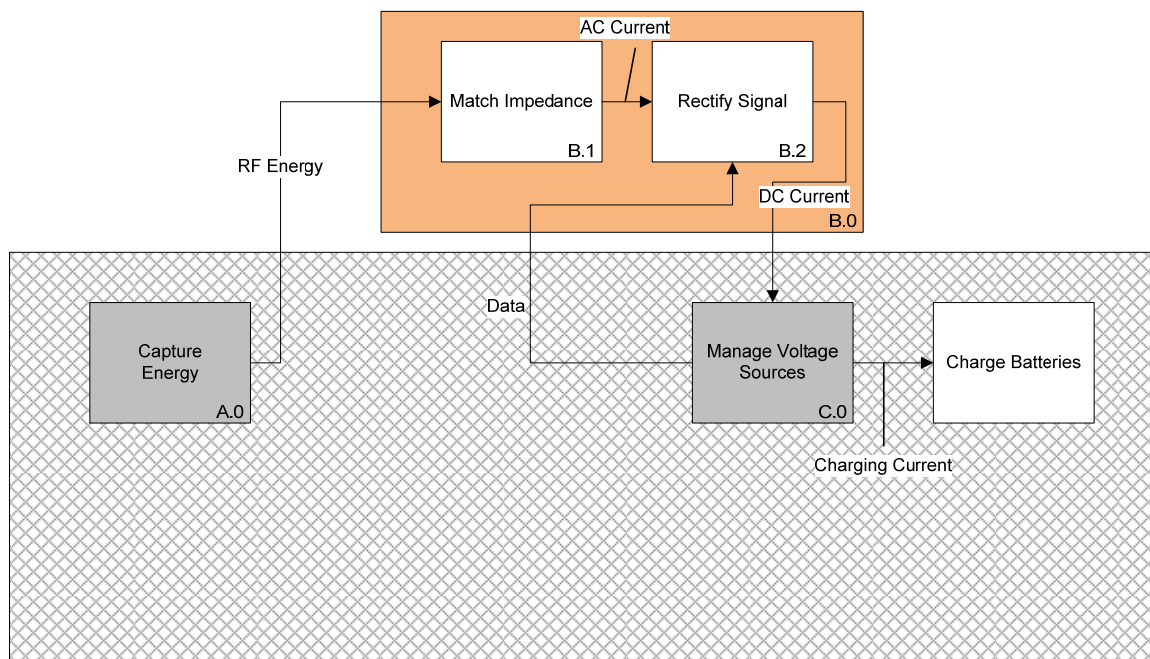


Figure 16. Rectify to DC (Level 1) Decomposition

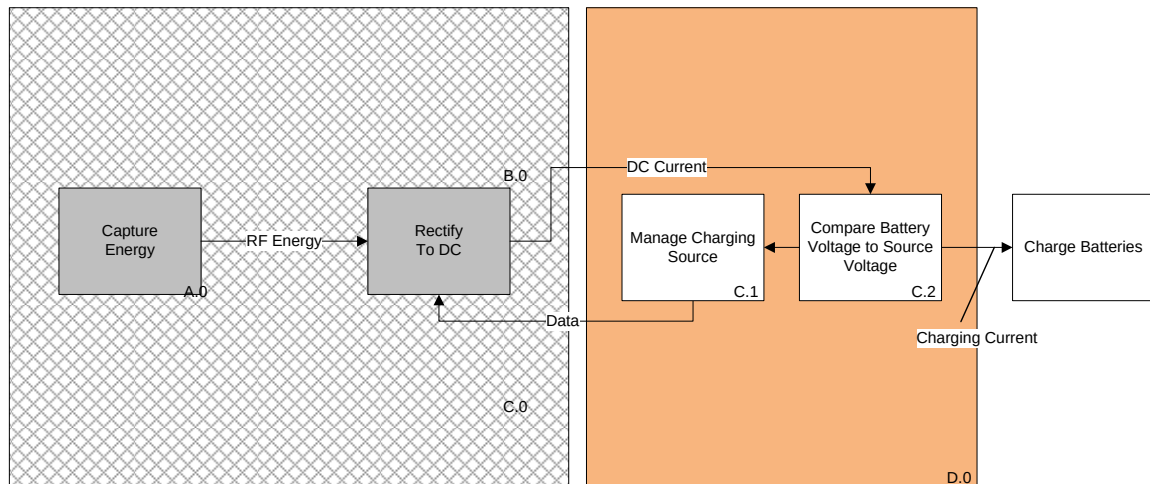


Figure 17. Manage Voltage Sources (Level 1) Decomposition

E. SYSTEM EVALUATION METRICS

Figure 18 provides a value hierarchy to summarize the functional decomposition and provide system objectives and metrics to be used for evaluation purposes. Each applicable block is also weighted for the Trade-off analysis (Buede, 2000). The weights provided imply the importance of that associated component meeting system requirements.

The Capture Energy functional block is equally vital to the other components because without adequate power density, the DX6 would not be able to remain in flight—mission failure. Likewise, if the energy captured is not properly rectified (Rectify Energy)—the DX6 would not be able to remain in flight—mission failure. By design, if the Manage Battery Charging the component fails, capture and rectified energy would not be applied to the battery bus—mission failure.

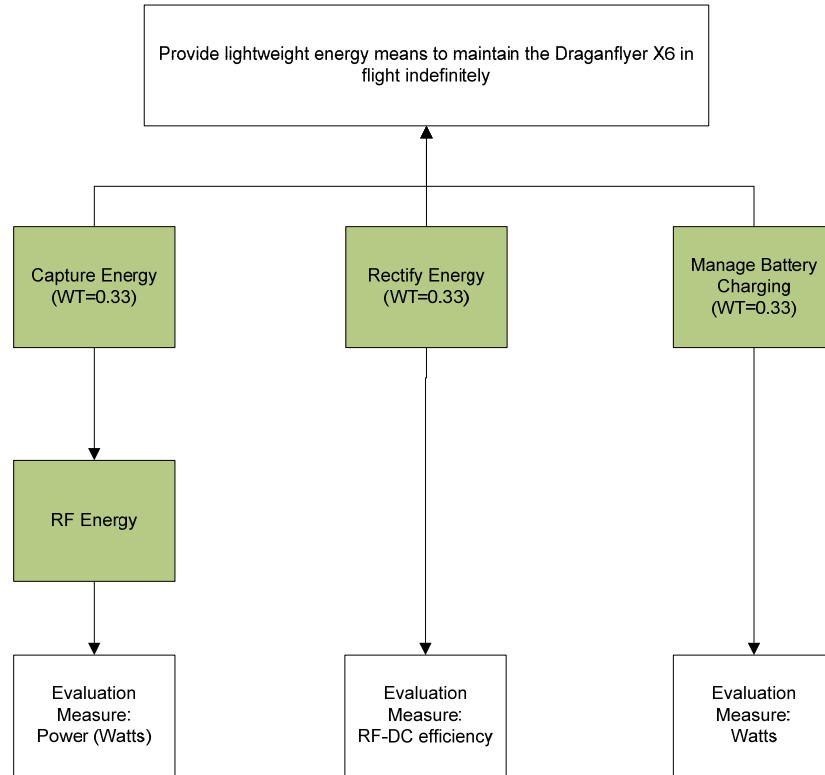


Figure 18. Value Hierarchy

Within the functional decomposition, three primary components are equally weighted. These primary components are established as a series network—a failure in one component results in total system failure, **Figure 19**. No information could be provided by the Draganflyer Innovations Corporation regarding reliability and maintainability. This is an area for future research beyond the scope of this thesis.

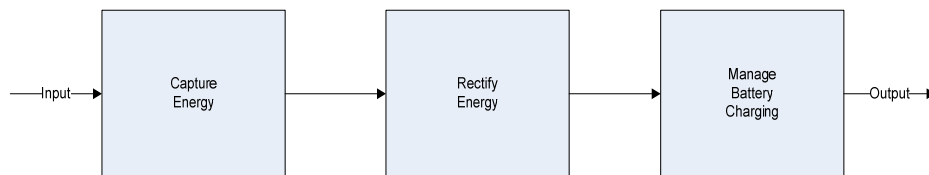


Figure 19. ECM Component Network (Series)

F. TRADE-OFF ANALYSIS

Mission accomplishment (ECM weight vs. Mission Performance) is the metric used for the trade-off analysis.

1. Mission Accomplishment

There are two main factors in mission performance/accomplishment – ability to remain on station and quality of video. The ECM is a system designed to keep the DX6 on station. Energy will be directed at the DX6 as it travels. The most limiting factor for mission accomplishment is weight, assuming successful ECM integration.

The trade-off is between quality of video and ECM weight. Although there is not a linear relationship between camera performance, which correlates directly to mission performance, and weight, it is possible to extrapolate mission performance based on camera information provided by the Draganflyer Innovations Corporation. **Table 6** provides a list of the available camera packages designed to work with the ECM and **Figure 20** illustrates this camera performance to ECM weight relationship. It should be noted that camera design and performance is an additional area of research, outside the scope of this thesis, which could significantly benefit the camera weight/mission performance trade-off.

Camera Type	Camera Weight (grams)	Available ECM Weight (Grams)
Micro Board Camera (No Zoom)	12	488
Med Quality (No Zoom)	153	347
Med Quality (Zoom Capable)	166	334
Hi Quality (Zoom Capable)	227	273

Table 6. Camera Weight vs. ECM available Weight

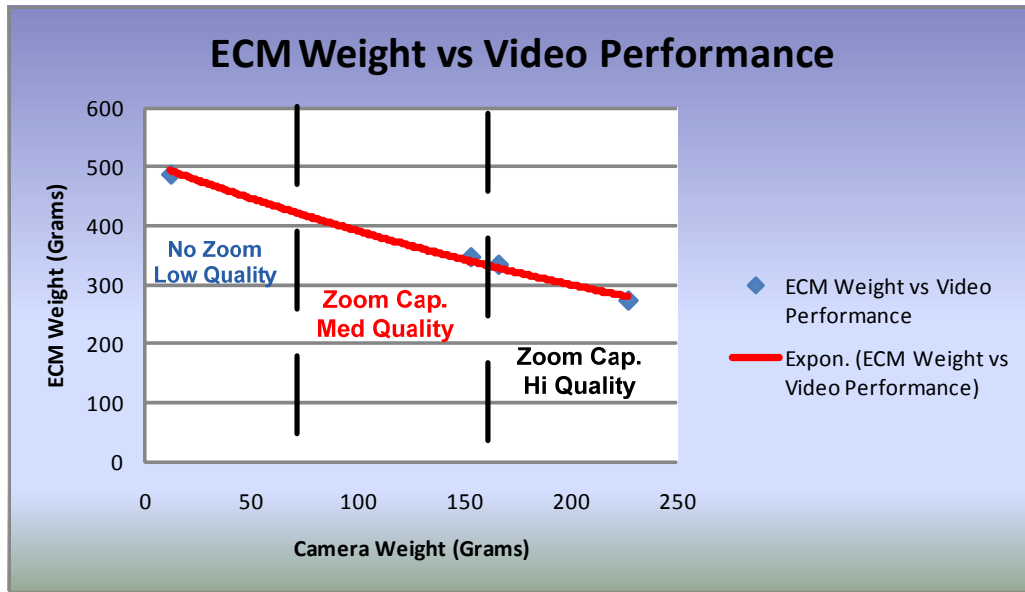


Figure 20. ECM Weight vs. Video Performance

Table 7 and **Table 8** provide a compilation of the data that obtained to determine the power density required of the ECM to provide energy for flight and camera equipment. **Figure 21** illustrates the power density load line.

Camera Type	Camera Peak Power (W) ($P=V \cdot I$)	(5-20VDC) Peak Current (mA)	Peak Flight Power	Total Power Required (Watts) ($P_{\text{camera}} + P_{\text{flight}}$)
Micro Board Camera (No Zoom)	2.96	200	240	243
Med Quality (No Zoom)	5.03	340	240	245
Med Quality (Zoom Capable)	12.43	840	240	252
Hi Quality (Zoom Capable)	13.32	900	240	253

Table 7. Camera Performance vs. Total Power Required

Camera Type	Total Power Required (Watts) (From Table 8)	Camera (grams) (From Table 7)	ECM (grams)	Ratio (Watts/gram) (Total Power / ECM weight)	Required Power Density (mW / cm^2) (Total Power / $1,600 \text{ cm}^2$)
Micro Board Camera (No Zoom)	243	12	488	0.498	152
Med Quality (No Zoom)	245	153	347	0.706	153
Med Quality (Zoom Capable)	252	166	334	0.756	158
Hi Quality (Zoom Capable)	253	227	273	0.928	158

Table 8. Camera Performance vs. Required Power Density

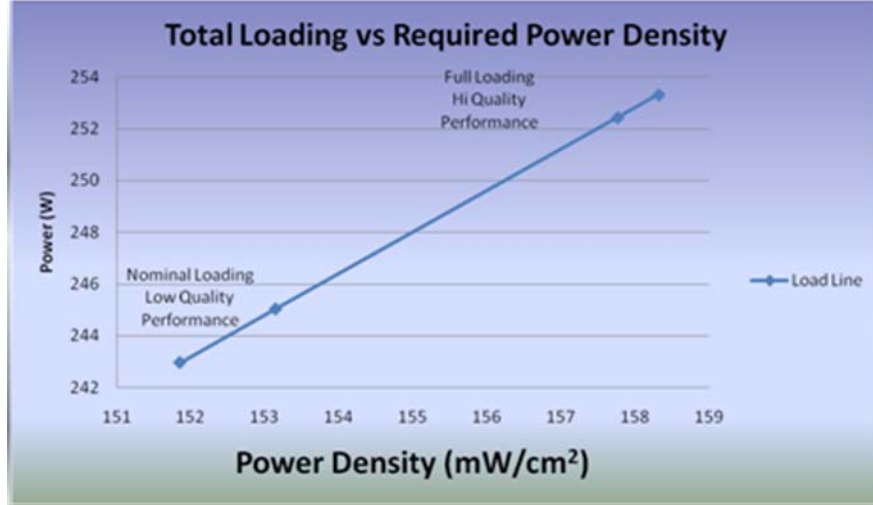


Figure 21. Total Loading vs. Required Power Density

Another area of consideration is frequency selection. Chapter II of this thesis discussed basic concepts of power transmission. An arrow analysis demonstrated with **Equation 5**:

$$P_t = P_r(d)^2 \lambda^2 \left(\frac{1}{A_R A_T} \right)$$

(5)

- As $\lambda \downarrow$ (decreases) : $P_t \downarrow$ (decreases)
- As frequency $\uparrow$ (increases): $\lambda \downarrow$ (decreases) – $P_t \downarrow$

Table 6 supported the arrow analysis and showed the higher frequencies required lower transmitter power. **Table 9** shows an additional analysis in the general properties of LOS wave propagation waveforms, which yielded:

- Microwave band is relatively experienced technology in power beaming
- Microwave band is less susceptible to water vapor (clouds) attenuation below 10GHz
- Microwave band make use of lightweight rectannas (rectifying antenna) at the receiver
- Lower frequency (compared to Laser) means larger transmitting antennas
- Laser band is less advanced in the technology field of power beaming

- Laser Band (THz band) is susceptible to water vapor attenuation
- Laser Band have smaller transmitter diameter requirements

Factor	Laser	Microwave
<i>Frequency</i>	<i>357 THz</i>	<i>2.4 GHz</i>
<i>Transmitter diameter</i>	<i><1m</i>	<i>>10m</i>
<i>Receiver System</i>	<i>Photovoltaic</i>	<i>Rectennas</i>
<i>Probable Power Required (Transmitter)</i>	<i>KW (10^3)</i>	<i>MW (10^6)</i>
<i>Technology Maturity</i>	<i>Developing</i>	<i>Maturing</i>
<i>Tolerance for Obstructions?</i>	<i>No</i>	<i>Limited</i>

Table 9. Laser vs. Microwave Energy Beaming (<http://www.mill-creek-systems.com/HighLift/chapter4.html>)

Depending on the application, both Laser and Microwave beaming systems are capable of meeting the user requirements. The microwave-based implementation is the preferred solution for the ECM, based on its tolerance for obstructions.

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V. CONCLUSION AND RECOMMENDATIONS

The proposed solution for this thesis is to utilize an Energy Capture Module (ECM) operating in the microwave band. The DX6 ECM is proposed as a scalable and Modular Open System (MOS) design concept that utilizes radio frequency (RF) energy to recharge the DX6 without the need of retrieval.

Conclusions

By utilizing energy beaming, it is feasible to have a module that meets the design constraints necessary to integrate with DX6.

Designing an ECM to utilize the microwave band also has significant benefits:

- Less susceptible to obstructions (water vapor, cellular antennas, power lines, etc)
- Capable utilizing the same power beam for communication (saves space and weight)

A significant advantage of the hybrid solution allows for extended buffering of the DX6 when it is not in line of sight of a RF energy beam. Utilizing the current DX6 configuration, a DX6 integrated with an ECM could operate on battery for approximately 20 minutes. This would allow the DX6 to maneuver to areas behind buildings until an RF energy beam could be aligned to the module (Tipler, 1987).

Recommendations

Preliminary research has indicated that in the long run the laser band ECM will likely be another feasible solution. Designing an ECM to utilize the laser band has significant benefits:

- Smaller Transmitter size (more portable and occupy less space)
- Lower Transmitter power requirements (more portable and more cost effective)

This thesis recommends that further research be conducted in both the microwave and laser bands.

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