Payload Design of Small UAVs

Scott Gruber, Hyukseong Kwon, George York, and Daniel Pack

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Abstract

This chapter presents the principles of payload design for small unmanned aerial vehicles (UAVs). Details of several payload design fundamentals to

S. Gruber (✉) · G. York
Academy Center for Unmanned Aircraft Systems Research, Department of Electrical and Computer Engineering, US Air Force Academy, Colorado Springs, CO, USA
e-mail: scott.gruber@usafa.edu; george.york@usafa.edu

H. Kwon
HRL Laboratories, Malibu, CA, USA
e-mail: hkwon@hrl.com

D. Pack
College of Engineering and Computer Science, University of Tennessee at Chattanooga, Chattanooga, TN, USA
e-mail: Daniel-Pack@utc.edu

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overcome various small UAV constraints imposed by stringent weight, power, and volume are discussed. Throughout the chapter, the efficacy of these principles is demonstrated with the actual payloads for a fixed wing UAV developed by the Center for Unmanned Aircraft Systems Research at the US Air Force Academy. Using the payload, the UAV autonomously searched, detected, localized, and tracked ground targets. The system requirements for the example application are closely related to those for other small UAV applications.

Keywords
Unmanned aerial vehicle (UAV) · Unmanned aircraft system (UAS) · Small UAV · Payload design · Payload subsystems · Payload budgets · Autonomous flight · RF link budget · Integration · System trade-offs

Introduction

In recent years, the USA has seen a growing UAV market for personal and professional use. The Federal Aviation Administration (FAA) has recently completed Small UAS Rule – Part 107 Federal Register (2016) – which defines the criteria and regulations for commercial use of UAVs. The FAA has also granted Section 333 exemptions to fly UAVs to businesses ranging from commercial filming to agriculture monitoring to mapping/land surveying to structural inspections FAA (2016)

Much of the current UAV use focuses on providing the user with optical imagery from different vantage points or into hard-to-reach areas. Though these applications represent the current use of small UAVs, they do not unlock the full potential of autonomous flying platforms. The Academy Center for Unmanned Aircraft Systems Research (ACUASR) has focused on developing autonomous UAV capability that expands the current UAV applications to enable a single or multiple small UAVs to perform dynamic missions. Specifically, ACUASR has focused its UAV autonomy research on the execution of intelligence, surveillance, and reconnaissance (ISR) missions with multiple UAVs working together. This chapter presents ACUASR's design approach for small UAV payloads to accomplish the higher level tasking while constrained to the volume and weight capacity that is available in a small UAV. Though this chapter focuses on the payload development of a fixed wing aircraft, much of the approach can also be applied to multi-rotor aircraft.

Researchers and developers in academia as well as in industry have worked on designing UAV payloads. Pastor et al. (2007) designed a low-cost embedded hardware/software architecture for micro UAVs, and Semke et al. (2007) suggested an approach to use remote sensing payload design for digital imaging on UAVs for educational development. Stuckel et al. (2011) proposed a payload design for a platform stabilization system to remotely deliver more stable imagery during flights. And Everaerts et al. (2004) provided various remote sensing payload designs for visual, infrared, laser, or atmospheric sensors. Recently, Cai et al. (2016) reported a radiation sensing payload design for a remotely controlled UAV.

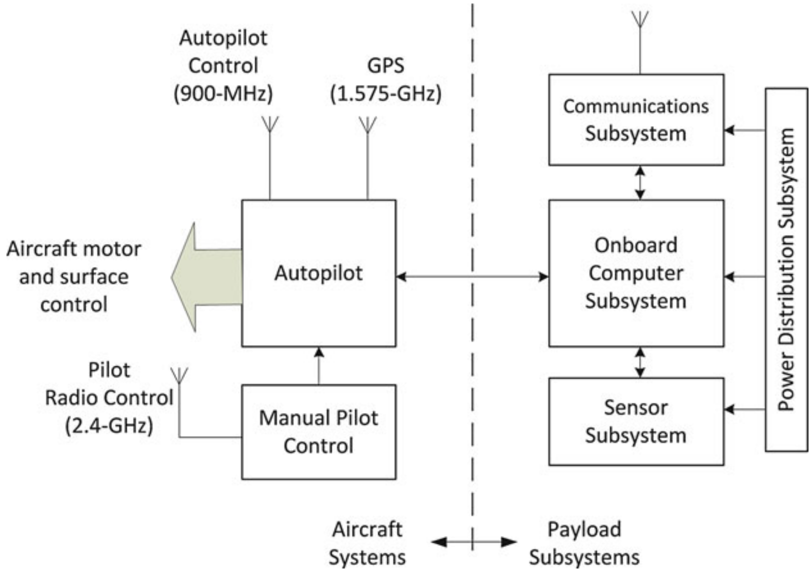

Fig. 1 Typical UAV subsystems

For the presentation, the chapter separates a small UAV into two parts: aircraft and payload (Fig. 1). The left side of the figure displays systems that this chapter considers as part of the aircraft. This includes the UAV autopilot, which provides attitude and position information to the payload and also receives commands from the payload. Note the three communication systems that a typical autopilot uses: a command and control system continuously communicating with a ground station operator (operating in the 900-MHz band on many autopilots), a global positioning system (GPS) which receives satellite signals at 1.575-GHz, and an RF link to a remote pilot, typically using an RC controller in the 2.4-GHz band. For this ISR application, the aircraft systems are on a separate power distribution system.

The right side of the figure contains the typical payload subsystems: a sensor subsystem to acquire information in flight (typically an electro-optical (EO) sensor); a communication subsystem for providing situational awareness to the ground operator and to receive commands from the same operator; an onboard computer subsystem for analyzing sensor data, executing tasks, and providing useful information to the ground operator; and a power distribution subsystem to support the above payload subsystems, typically using batteries.

These payload systems must meet the volume and weight constraints dictated by the chosen aircraft. Figure 2 presents two types of aircraft. The left image shows a multi-rotor aircraft. Due to its limited payload capacity, much lighter payload systems are chosen. The right side is a fixed wing aircraft with much higher payload carrying capacity. For a small UAV, the constraints of volume and weight and also close proximity of payload components drive additional considerations

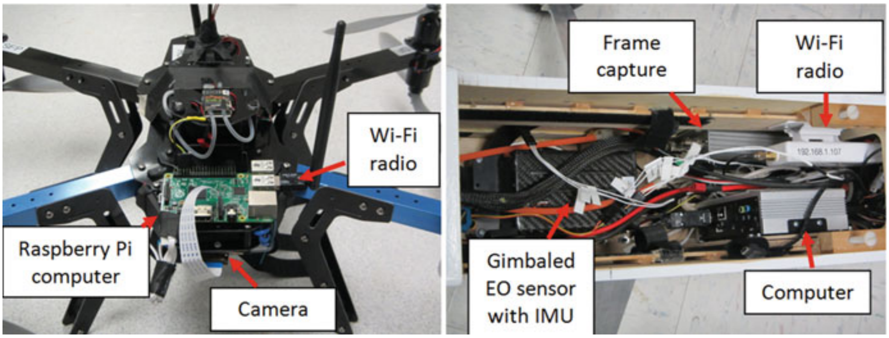

Fig. 2 Matching payload to vehicle capability. The *left* image is a multi-rotor aircraft with a Raspberry Pi computer acquiring images from the camera and sending them to a ground station via the low-power Wi-Fi radio. The right image is of the bay below the wing on a fixed wing UAV. It can carry a gimbaled EO sensor which provides analog images to a frame capture board for the onboard computer image processing and analysis. Imagery and mission status is sent to the ground station over a higher power Wi-Fi radio

whose objectives may contradict each other: electronic components must avoid electromagnetic interference (EMI) interactions; electrical power is limited by the space and weight available for energy storage devices such as batteries; total payload operational time is limited by the available power; processor speed is limited by the weight and power available; and sensor capabilities such as video frame rate and image resolution are limited by its weight allocation.

The constraints of volume and weight play critical roles in the following major trade-off design decisions for a small UAV payload:

- Level of autonomy (onboard control decisions) versus complete or partial human operator control
- Sensing autonomy (onboard sensor output processing) versus available communication bandwidth with a ground station
- Level of autonomy (onboard capability) versus available power onboard for flight duration time
- Minimalist design versus flexible and adaptable design
- Optimal complex systems versus simple systems

Designing a small UAV payload involves trade-offs among the basic UAV subsystems shown in Fig. 3. Making the design decisions is nontrivial; decisions made for one subsystem often affect the designs of other subsystems. In addition, while managing the balance among subsystem designs, the overall small UAV system constraints of weight and volume must be maintained. For example, if an extensive image processing algorithm is executed on images at a fast rate to meet the requirement of a mission, the onboard computer needs to handle the needed computational load. The larger the computer's computational needs, more power

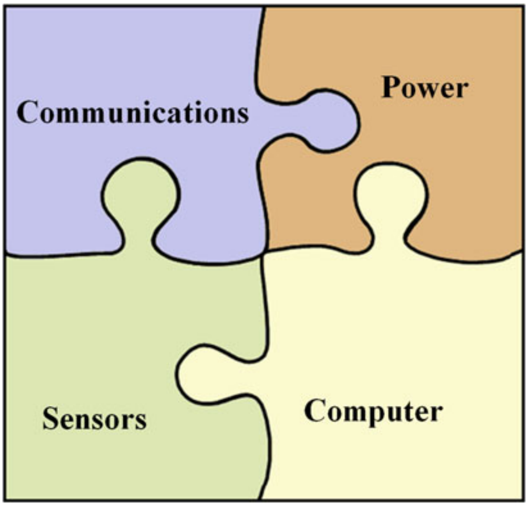

Fig. 3 Major payload subsystems

and cooling for the computer to complete the task is necessary. Since the payload battery capacity cannot be increased, due to the overall weight restriction, the added computational requirement will likely result in the mission time being reduced. If mission time is not negotiable, can another choice be made that still accomplishes the goal of the mission? Can the image processing rate be reduced, or can a less computational image processing algorithm be used? These are typical questions that must be answered before any design is chosen.

We present a procedural method to design an integrated payload that maximizes performance in a small UAV package. The chapter is organized to:

(a) Define the mission requirements of a payload (section "Payload Mission Requirements").
(b) Create preliminary weight, power, and volume budgets for a payload (section "Payload Design Budgets").
(c) Start an iterative design of payload subsystems, constantly interacting among all subsystem designs to ensure that performance is maximized within system constraints (section "Subsystems Design").
(d) Address additional issues that can affect the payload design (section "Other Payload Design Considerations").

Throughout this chapter, examples are provided to help explain the related concepts. There is also an underlying emphasis to ensure EMI does not contribute to the loss of GPS signals. For our applications, UAVs rely on GPS signals for navigation, making it necessary to have a reliable GPS system.

Payload Mission Requirements

Before a detailed design for an ISR mission can be developed, the requirements of the payload must be first defined. Some questions that should be asked at this stage that will affect a small UAV payload design are:

- What is the flight duration required for the mission?
- What is the specific task or a list of tasks required of the mission? For example, searching for specific targets, setting up surveillance posts, providing a communications relay, etc.
- What are detailed mission subtasks? How large is the search area?
- How long will the payload systems need to operate on the ground before the flight commences?
- How many UAVs will be in flight?
  - If multiple UAVs, how is collision avoidance incorporated? For a small UAV, altitude separation is typically used so that avoidance hardware isn't necessary.
- What are the target characteristics and the accuracy of localization for the ISR mission?
  - Moving or stationary targets
  - Number of targets
  - Target separation
  - Size, shape, and color of targets
- What are the allowed frequencies that can be used for communications between UAVs and the ground station?
- What is the maximum distance from the ground station that the UAVs will be operating?
- Will other devices be operating in the same area that can cause communication interference?
- What are the situational awareness requirements of the ground station operator?
  - Imagery refresh rate
  - Image quality and size
  - UAV position, mission status, and health
- What are the environmental requirements (vibration, shock, humidity, and temperature)?

Payload Design Budgets

The payload design is governed by two limiting factors: payload weight and volume. Power, in the form of batteries, is a large contributor to the payload's weight. Any reduction in power requirements of the payload subsystems will result in either an overall weight reduction or an increase in the possible flight/mission time. Thus, in the flow diagrams used in each of the subsystem design sections, a reference to WPV

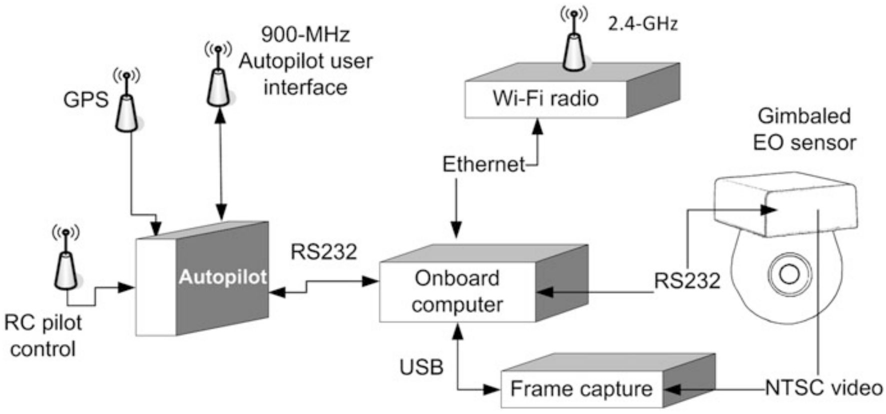

Fig. 4 An example of payload hardware design

is used to represent weight, power, and volume. Note that cost is another important factor in developing a design. This is specific to each small UAV application and is not addressed in this chapter.

When developing a preliminary design budget, an investigation of likely components needs to be completed. These components can then be used to determine the preliminary allocation of weight and volume. Figure 4 is an example payload hardware design including major components and I/O between components. To start the payload sizing, a preliminary power budget is useful since battery weight is a major weight contributor.

The Power Budget

For a small UAV gasoline propulsion system, having an onboard generator is unlikely due to the weight constraint, so a battery is necessary to support the payload system. If the propulsion system is electric, the propulsion batteries are typically used just for propulsion to maximize flight time, again requiring the payload to have its own battery. Note that if the payload has small power requirements, the small UAV design may opt to use the propulsion batteries to support the payload with the understanding that the flight duration will be impacted. This section will focus on an example payload system with its own battery.

An estimated payload is used to compute an overall payload power requirement. Table 1 presents an example payload using an atom-based processor, a 2.4-GHz radio, and a gimbaled EO sensor system (with frame capture board) as the key payload components. Since this table is developed early in the design, a 30% management reserve is added to the power for use in case it is needed as the design progresses. Based on this analysis, the onboard computer system (processor and disk) has a 13.2-W budget, the communications system has a 4.1-W budget, and the EO sensor system has a 17.5-W budget (including frame capture board). Note

Table 1 Example power budget

Component	Voltage	Current	Watts
Onboard computer and internal SSD	12	1.1	13.2
W-Fi radio (50% duty cycle)	12	0.34	4.1
EO sensor with gimbal	12	1.13	13.5
Frame capture board	5	1	4.0
Total required payload power			34.8
		Efficiency	Watts
Adjusted for efficiency of DC-DC converter		0.9	38.7
Adjustment for 30% management reserve		0.7	16.6
Total allocated power			55.3
		Batt volt	Needed current
Battery voltage and current for required power		14.8	3.7
		Batt AH	Available hours
Lithium polymer battery amp hours (AH) and available operational hours		4.2	1.1

that the high current requirement for the EO sensor includes the gimbal and inertial measurement unit (IMU). Also note that the current requirement for the Wi-Fi radio assumes it is transmitting approximately 50% of the time. The available battery life is 1.1 h. If the combination of ground time and flight time usage is close to 1.1 h, a higher capacity battery should be employed.

The Weight Budget

The maximum available payload weight, an important design constraint, is predetermined by the aircraft's lift and gross weight limits. Using the same components used for the power budget, Table 2 shows a preliminary weight budget. This example assumes that the small UAV allocation for maximum payload weight is 7 lb. In this case, the management reserve is 20%. The resulting weight budgets are 23.1% for the computer subsystem (includes the SSD), 3.9% for the communications subsystem, 37.4% for the sensor subsystem, and 15.6% for the power subsystem. Note that the large weight allocation for the sensor system includes a gimbal with IMU. If the aircraft doesn't have sufficient payload allocation to support this weight, an alternative sensor and mission approach would be needed.

Volume Allocation

When considering the volume available for payload components, it is not sufficient to simply allocate volume for each component. Instead, components must be

Table 2 Example weight budget

Component	Weight (g)	Percent weight (%)
Onboard computer and internal SSD	710	23.1
2.4-GHz radio, cables, and antenna	120	3.9
EO sensor with gimbal and frame capture	1150	37.4
Power system (battery, DC-DC, wires)	480	15.6
Total required payload weight	2460	
Adjustment for 20% management reserve	615	20.0
Total weight estimate	3075	100
UAV payload weight allowance (7 lb)	3175	
Additional weight buffer	100	

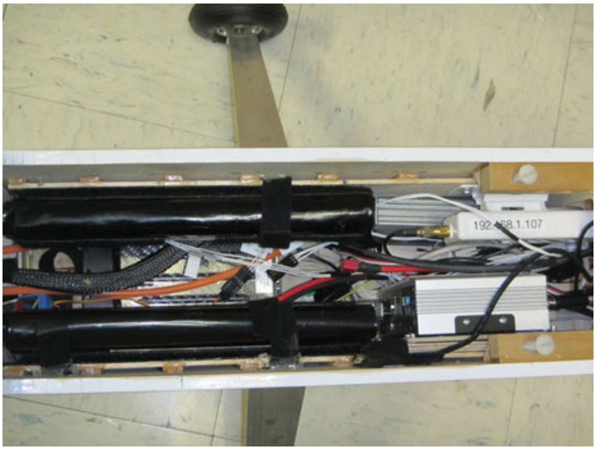

Fig. 5 A sample payload placement for fixed wing aircraft

configured within the payload compartment(s), placed for proper payload assembly, and tested for any electronic interference to each other. Furthermore, components must be arranged so that the aircraft center of gravity is maintained for stable flight. For example, Fig. 5 shows the payload bay below the wing of a small UAV. This area contains the heavier components of the payload as described in the right image of Fig. 2 and also the propulsion batteries. Placing the heavier objects near the center of gravity (CG) minimizes longitudinal moments. This payload area is still heavier toward the tail, so the payload battery and autopilot are located in the front of the aircraft to ensure CG is maintained.

Subsystems Design

The following sections use a flowchart that represents the design flow for each of the four subsystems shown in Fig. 3. The number in each flow element corresponds to the item in the accompanying list that further explains the flowchart elements.

Communications Subsystem

The design flow of the communications subsystem is shown in Fig. 6.

1. Define mission constraints.
   (a) Allowed frequencies. Unless licensed radios are available, a UAV will likely be using the unlicensed ISM (industrial, scientific, and medical) bands. For UAVs, the 902–928-MHz, the 2400–2483.5-MHz, and the 5725–5850-MHz bands are commonly used. These bands can provide one to multiple 20-MHz channel bands, and compliant radios are readily available. Transmission power is restricted per FCC regulations; radios and antenna gain need to be selected that comply with these regulations. Note that the 902–928-MHz band is frequently used for the autopilot wireless link.
   (b) Maximum distance. This distance is used to determine the link budget.
   (c) Number of UAVs in flight will determine if a multi-hop network is possible and the total bandwidth available at the ground station.
   (d) Other devices operating in the same area create noise and limit the communication system range if they are broadcasting over the same frequencies.
   (e) Situational awareness requirements of ground station operator drive the bandwidth requirements of the system. A number of key questions to be asked are:
      i. What command and control messages are necessary and what is the update rate of the messages?
      ii. What aircraft status messages need to be reported to the ground station? i.e., aircraft health, stage in mission, etc.
      iii. What size and compression factors of images are acceptable? Imagery is the largest consumer of the communication bandwidth. If a communication link is broken during a mission, imagery collected during the lost link may not be useful for the operator. If the imagery is sent using Transmission Control Protocol (TCP), the images have guaranteed delivery. During a lost link, these images are placed in a transmission queue and sent when the link is reestablished. Critical command and control messages need to wait until the queue is emptied of images. If only the current imagery is needed for situational awareness, imagery should be sent using User Datagram Protocol (UDP) which does not guarantee delivery. Thus, the imagery will not sit in a queue, and command and control messages are not delayed when the link is reestablished.
      iv. If multiple UAVs are used, how does the imagery need to be presented? To minimize the overall bandwidth, a thumbnail image can be displayed to the operator. The operator then has an option to select a thumbnail to start receiving larger imagery, reducing the overall system bandwidth.

   Table 3 is an example calculation used to estimate the bandwidth requirements. In this example, four UAVs converse with the ground station. Only one operator-selected UAV sends high-resolution imagery (320×240 pixels) to the

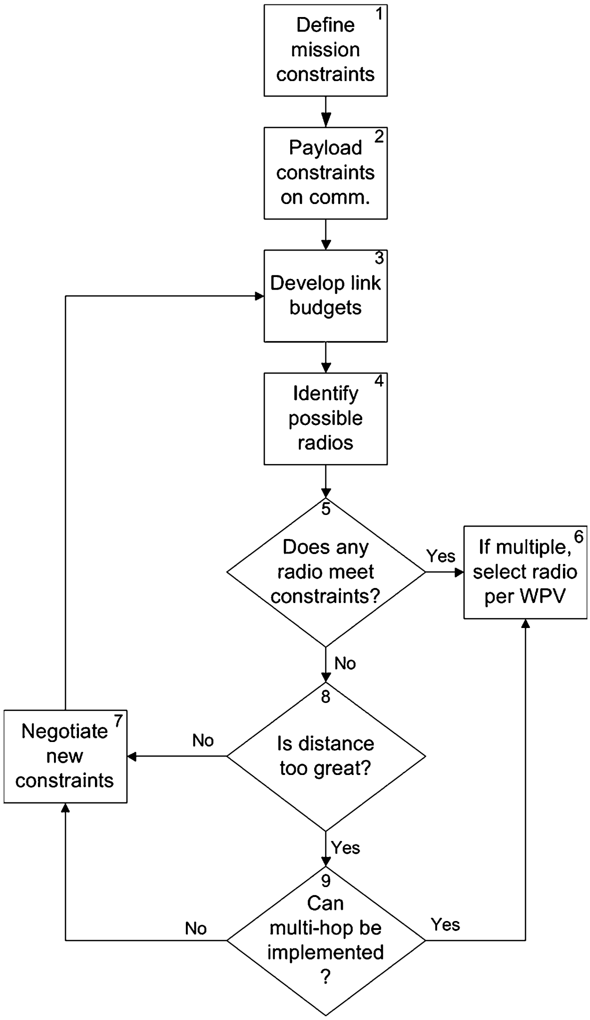

Fig. 6 Communications subsystem design flow

ground station, and all four UAVs send thumbnail images. The "Number/s" column defines how many messages per UAV are allowed, and the "Total streams" column is based on the number of UAVs in the system plus an increase of 25% to assume 25% of the messages are being relayed through another UAV (multi-hop). An assumed 25% efficiency for the system accounts for message overhead and resends of lost messages. The total message bandwidth required is then compared to available data bandwidths for 802.11-g protocol. The 6-Mb/s system does not have the capacity, and a 12-Mb/s system is required. Since imagery is the largest bandwidth consumer, a reduction in frames per second could get the bandwidth requirement to a more manageable size.

Table 3 Estimated communication bandwidth requirements

Information	Size (KB)	Number/s	Total streams	Total KB/s
Image 320 × 240 @ 10% comp	20	10	1.25	250
Image 80 × 60 @ 30% comp	1	4	5	20
Control messages	0.1	5	5	2.5
Health messages	0.1	1	5	0.5
Ground station messages	0.1	2	5	1.0
Other	0.1	1	5	0.5
Total				274.5
Bandwidth efficiency	25%			
Bandwidth available (kb/sec)	Kb avail	KB avail		Usage
6000	1500	187.5		146%
12,000	3000	375		73%
24,000	6000	750		37%

2. Define payload constraints on the communications system. These are constraints generated by the other components of the payload. Some of the questions that must be answered are:
   (a) If multiple UAVs are used, does one UAV need to communicate with another, or do all UAVs communicate directly with the ground station? If UAVs communicate with each other, is the link between UAVs direct or will the messages be routed through an access point at the ground station?
   (b) What is the weight allocation for the communications system?
   (c) What is the power allocation for the communication system?
   (d) What are the input/output (I/O) interfaces available from the onboard computer?
3. Develop a communications link budget. A communications link budget is a method to estimate how well a communications channel will work for a specific system. It is a good tool for comparing multiple radios, antenna, and frequency bands. This section will not provide a detailed description but gives an example calculation.

   The link budget is based on the Friis equation (1946): $P_R = P_T G_T G_R \left(\frac{\lambda}{4\,\pi\,d}\right)^2$. The power received by a radio, P_R, is equal to the power transmitted by a second radio, P_T, that is focused by the gains of the transmit and receive antenna, G_T and G_R, but is attenuated by the distance the signal has to travel. The last term, $\left(\frac{\lambda}{4\,\pi\,d}\right)^2$, is usually referred to as the *free space loss*: the λ represents the wavelength of the carrier wave, and d is the distance between the antennas.

   The equation can be expanded to include additional losses and represented in decibels to simplify the calculations. $P_{\mathrm{RdB}} = P_{\mathrm{TdB}} + G_{\mathrm{TdB}} + G_{\mathrm{RdB}} - L_{\mathrm{FSdB}} - L_{\mathrm{CbldB}} - L_{\mathrm{PoldB}} - L_{\mathrm{PntdB}}$, where transmit and receive gains are the maximum gains of the antenna, free space loss (L_{FS}) is defined above, cabling losses (L_{Cbl}) are due to the interconnections between the radio and the antenna, polarization loss

Table 4 Communications link budget problem definition

Parameter	2.4-GHz radio	900-MHz radio
Required receive power for 11 Mb/s (dBm)	−92	−90
Transmit power for 11 Mb/s (dBm)	28	28
Maximum distance (mile)	1	1
Ground station antenna gain (dBi)	4	4
Aircraft antenna gain (dBi)	2	0
Maximum point error	Half-power beamwidth	Half-power beamwidth
Maximum bank angle (°)	15	15
Radio to antenna cable losses at each end (dB)	0.5	0.5

(L_{Pol}) is due to misalignment of the electric fields, and pointing losses (L_{Pnt}) are due to misalignment of the physical antenna. The actual gain of an antenna varies as measured around the antenna. The typical antenna used on a UAV are dipoles and monopoles which have a gain pattern similar to a doughnut, with the antenna being the axle of the doughnut. These antenna are referred to as omnidirectional due to equal gain in all directions away from the antenna in a plane perpendicular to the antenna.

The design of an antenna generates an alignment of its electric field, referred to as polarization. The most common type used in UAVs is linear polarization, where the electric field aligns with one plane. In the case of a dipole antenna, the field is aligned with the length of the antenna. Thus, for a UAV with a half-wave dipole antenna mounted vertically to the fuselage, the ground station antenna should also be mounted vertically. During flight, the antenna will not always be aligned due to the pitch or roll of the aircraft. This misalignment is referred to as polarization loss and is defined as $20 \log_{10}(\cos(\theta))$, where θ is the maximum misalignment angle. For missions where altitude is held constant, θ can be approximated by the maximum roll angle allowed by the autopilot.

Even if the antenna have no polarization loss, there will still be losses because the aircraft is at a different altitude from the ground station, and the aircraft rolls away from the ground station. Figure 7 is an example of these two conditions. The blue outline is the gain pattern for a one-half wavelength dipole antenna, the red line is the line of sight, and the black lines mark the point in the antenna gain pattern where the gain is one-half of the maximum pattern gain. antenna should be selected to ensure that the geometry of the UAV system stays within these one-half power or 3 dB points. When maintained, the maximum pointing losses can be assumed to be 3 dB.

The use of the link budget will now be demonstrated through an example. Two radio systems are being compared, a 2.4-GHz radio and a 900-MHz radio. A data bandwidth of 11 Mb/s needs to be maintained, resulting in transmit and receive powers presented in Table 4. Other system parameters are also defined in Table 4.

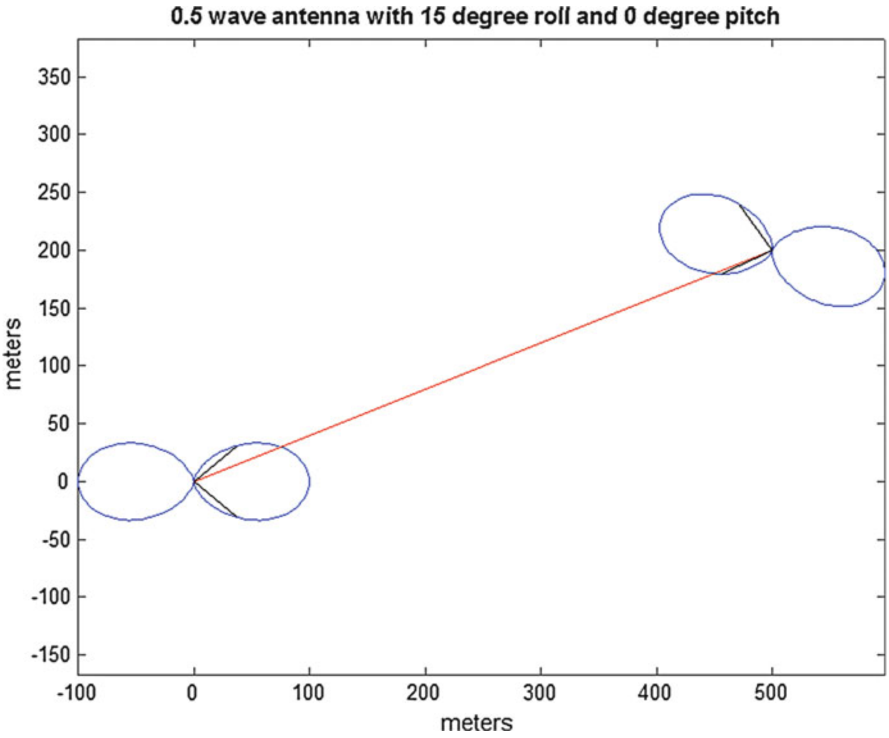

Fig. 7 Antenna pointing loss

Table 5 presents the solution of the link budget. The free space losses are calculated as:

2.4 – GHz radio: For center frequency of 2.45 GHz

$$: 20^{*}\log_{10}\left(\left(4\pi^{*}1609\right)/0.122\right) = 104.4\ \text{dB}$$

900 – MHz radio: For center frequency of 915 MHz

$$: 20^{*}\log_{10}\left(\left(4\pi^{*}1609\right)/0.328\right) = 95.8\ \text{dB}$$

And the polarization loss is calculated as:

$$\text{Polarization Loss: } 20^{*}\log_{10}\left(\cos\left(15^{\circ}\right)\right) = -0.3\ \text{dB}$$

A good link margin should be above 10 dB. In this case, both radios exceed the link margin. Since both systems have sufficient link margin, other factors should be considered such as in-band interferers. If the autopilot wireless link uses the 900-

Table 5 Communications link budget example solution

Parameter	2.4-GHz radio	900-MHz radio
Power transmit for 11 Mb/s (dBm)	28.0	28.0
Ground cabling loss (dB)	−0.5	−0.5
Ground station antenna gain (dBi)	4.0	4.0
Ground pointing loss (dB) (half power pointing error)	−3.0	−3.0
Free space loss (dB)	−104.4	−95.8
Polarization loss (dB)	−0.3	−0.3
Aircraft pointing loss (dB) (half power pointing error)	−3.0	−3.0
Aircraft antenna gain (dBi)	2.0	0.0
Aircraft cabling loss (dB)	−0.5	−0.5
Power received (total of above) (dBm)	−77.7	−71.1
Required receive power for 11 Mb/s (dBm)	−92.0	−90.0
Link margin (dB)	14.3	18.9

MHz band, there is potential interference for that radio. It would then be better to choose one of the 2.4-GHz channels.

4. Identify possible radios. The link budget in Step 3 guides the choices of possible radio solutions. After possible radios are chosen, additional link budget comparisons can be made for final selections. Other considerations when choosing a radio are:
   (a) What I/O interfaces are available from devices connected to the radio? Typical embedded radio interfaces are mini-PCI and PCI-Express, and external radios may use USB or Ethernet.
   (b) What antenna connectors are available on the radios? A smaller connector, such as an SMA, is much lighter than the bulky N connector.
   (c) Select antenna based on required coverage of the mission area. Directional antenna are not feasible on a small UAV because there isn't a sufficient weight budget to carry a pointing device. Also, an increase in directionality of an antenna is an increase in antenna size. Thus, small UAVs use omnidirectional antenna. On the other hand, the ground station can use a directional antenna if the UAV mission area is away from the ground station such that the UAVs will remain within the 3 dB beamwidth of the antenna.
5. Does any radio meet the communication system constraints?
6. Introduce WPV factors to make the final decision. Reduction in weight and power can either leave more allowance for other payload subsystems or increase flight time.
7. If a solution cannot be found, identify what can be supported and work with the customer to develop new constraints. Multiple design loops are typically required to develop a robust system.

8. Is the only constraint that wasn't met "having insufficient link margin at the required distance"?
9. A multi-hop solution may be possible. In a multi-hop solution, messages from a distant UAV are relayed by intermediary UAV. Note that this requires a doubling of bandwidth for any multi-hopped messages since they are sent first by the originating UAV and then again by the relaying UAV. Though standard 802.11 a/b/g access points do not support multi-hop and typically require an ad-hoc network to be created, some radios have a proprietary method of providing multi-hop transparently to the user Ubiquiti (2013).

Onboard Computer Subsystem

Figure 8 shows the design flow for selecting the computer subsystem.

1. Define mission constraints.
   (a) Mission time. Define how long the onboard computer subsystem needs to operate, both prior to takeoff and during mission.
   (b) Environmental requirements affect the selection of the computer subsystem.
      i. Will the interconnection of the computer subsystem with other subsystems handle shock and vibration?
      ii. Will a hard disk be a viable solution or must a solid-state disk (SSD) be employed?
      iii. Do expected humidity and temperature conditions affect the computer subsystem choice? Small computers developed for industrial applications are typically more robust and do not require external cooling Advantech (2017).
2. Define payload constraints on the computer subsystem.
   (a) What are the computing requirements for processing images?
   (b) What are the computing requirements for control algorithms?
   (c) What are the computing requirements for processing sensor outputs?
   (d) What I/O ports are needed to interface to autopilot, sensors, and communications systems?
   (e) What operating system is necessary to support software requirements?
   (f) What is the weight allocation for the computer subsystem?
   (g) What is the power allocation for the computer subsystem?
3. Develop performance budgets. Table 6 is an example that assigns the computer resources to different software tasks, including a 20% reserve for future enhancements.
4. Look for possible computer solutions that meet the performance budgets. The solution must also consider storage requirements.
5. Were any computers found that meet the requirements?
6. If there were, does the computer subsystem generate any GPS noise?

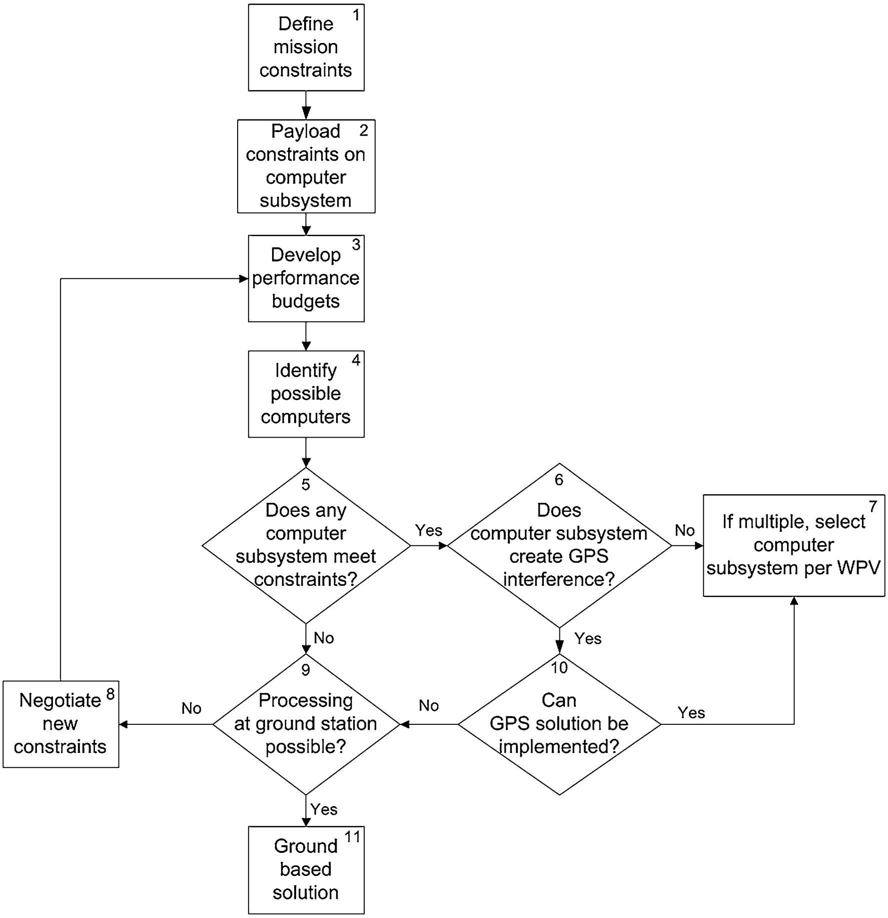

Fig. 8 Onboard computer subsystem design flow

Table 6 Example of aircraft software budget table

Priority	Component	CPU allocation (%)
1	Image capture	10
2	Planning and control	10
3	Image processing	40
4	Data fusion	15
5	Housekeeping	5
	Reserve	20
	Total	100

7. If multiple choices exist, select the best choice using WPV factors. Reduction in weight and power can either leave more allowance for other payload subsystems or increase flight time.
8. If no viable computing solution can be found, new constraints must be negotiated with the customer.
9. If an onboard computer solution can't be found, is a ground solution viable?
10. Can a solution to the GPS EMI issue be found?
    (a) In an attempt to minimize weight, a computer without an enclosure may be selected. Without the enclosure, the Faraday cage that contains the EMI is not present, and noise may interfere with GPS.
    (b) Directly connecting an external SSD to the computer via the serial advanced technology attachment (SATA) bus will generate severe GPS noise. SATA generates broadband noise to over 2 GHz. If requiring an external drive, either choose a parallel bus or incorporate the computer and SSD enclosures that support E-SATA and use the shielded E-SATA cable between them.
11. Areas to consider for a ground-based computing solution:
    (a) A faster computer that doesn't need to meet weight requirements could be available for ground use. If performing ground-based image processing, high-resolution images from the aircraft may be required. Higher resolution images require greater communication bandwidth, which increases with the number of UAVs in use. Can the communications system handle this bandwidth?
    (b) With all processing on the ground, what happens to the success of the mission if messages are lost?

EO Sensor Subsystem

Though other sensors may be used, the EO sensor is predominantly employed in small UAVs. This section presents design considerations for the EO sensor, but the methods can be readily applied to other types of sensors. The EO sensor subsystem includes the sensor hardware, frame capture hardware, and any required gimbal mechanism for panning the sensor. If the gimbal system uses a dedicated IMU, an additional weight allocation is required. Instead, a small UAV could use an autopilot to provide the aircraft attitude to the image processing system to geo-register the image. Figure 9 presents the design flow of an EO sensor subsystem.

1. Define mission constraints.
    (a) If multiple UAVs are used, is collision avoidance achieved through altitude separation? To simplify the image processing algorithm, a variable zoom camera could be employed and the zoom level set for a specified flight altitude to force the target size to be consistent for an algorithm.
    (b) Based on the target characteristics and ground coverage,
        i. What image processing techniques need to be employed?
        ii. Will sensor panning be required?

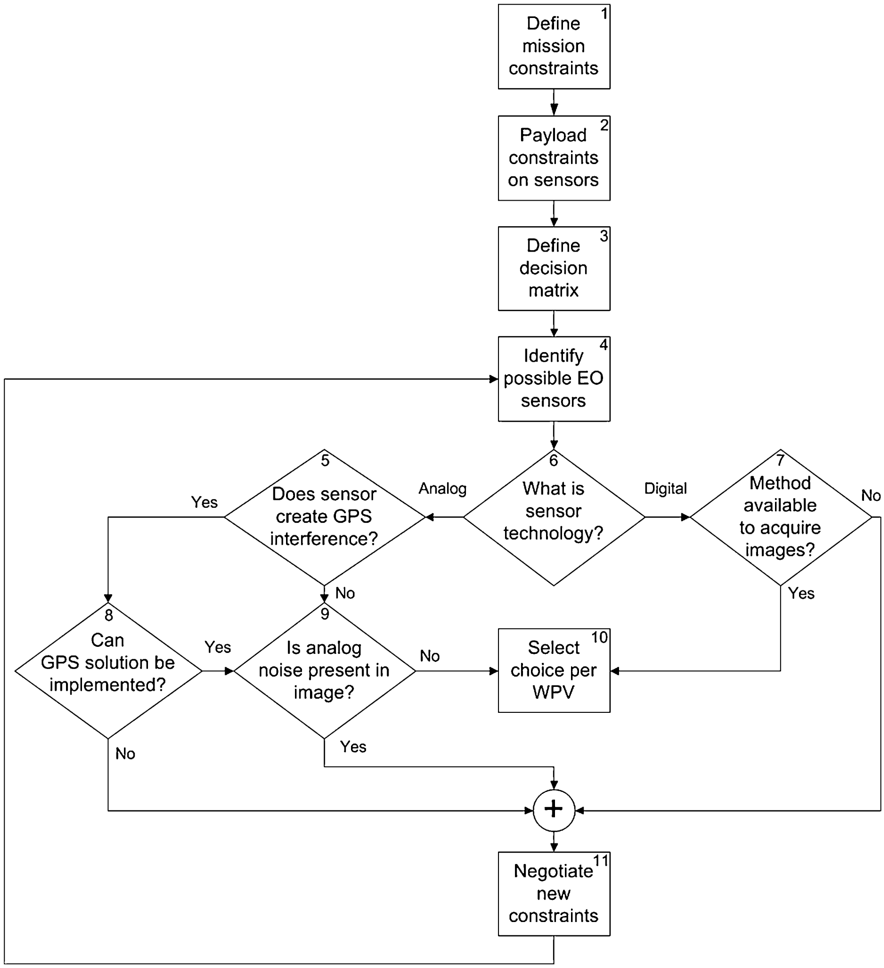

Fig. 9 EO sensor subsystem design flow

iii. What image quality and size are needed?
iv. How many images per second are required to process?
(c) Environmental requirements.
i. Will aircraft vibration impact image quality and registration?
ii. Will the sensor meet humidity requirements? Will it meet shock requirements?

2. Determine constraints from the rest of payload. The EO sensor needs to comply with its allocation of weight, power, and volume, but it also drives the computer's computational requirements. The image processing algorithm selection needs to consider a reasonable computer processing capability for

Table 7 Comparison of pan-tilt-zoom camera systems

	Security camera	Gimbaled camera with IMU and frame capture board
Pixel resolution	640 × 480	320 × 240 (after conversion)
Frame rate (fps)	30	30
Video signal output	JPEG	H.264, jpeg
Pan/tilt	+/−70°/+/−52° (electronic) – Mounted with 15° tilt	360° continuous/+23 – −203° (mechanical)
Zoom	3× electronic zoom	31× optical
Weight (g)	504	1150
Dimension (W × L × H (mm))	89 × 94 × 77	114 × 114 × 178
Power consumption (W)	3.6	14.0

a small UAV. Sensor fusion techniques may be employed to account for inaccuracies in the image processing results.

3. Develop a decision matrix for the EO sensor. Table 7 presents specifications for two types of EO sensors. The security camera has limited zoom and pan capability but provides digital images for image processing and has fairly low power consumption and relative weight. The gimbaled camera provides an analog output, so the images must be captured from the streamed video to produce digital images for processing. The gimbaled camera has high zoom capability, but because the analog video complies to the National Television System Committee (NTSC) standard, odd lines and even lines of the image are alternated. Because the UAV is in motion, the slight delay between odd and even lines causes jaggedness in any edges in the image. To mitigate this issue, only the odd lines can be analyzed, so that the 640 × 480 pixel image from the frame capture board is reduced to 320 × 240 pixels.

   Table 8 presents a decision matrix that helps determine the best choice of sensors. The parameter column lists the metrics that are important for this application. The parameter weight column defines how important that parameter is for this application. For our application, the UAV tracks a moving vehicle. To calculate the best estimate of the vehicle's location and direction of travel, a high number of images that contain the target are needed. Thus, the pointability of the sensor is highly valued. Because this sensor is going on a fairly large UAV, the parameters of weight and volume have less influence to the design decision. To create the score, the parameter weight is multiplied by the assigned rating. In this case, the gimbaled camera is the better choice. If the vehicle had minimal payload capacity, the parameter weights would have been chosen differently.
4. Define possible EO sensors. Two general types of EO sensors are typically employed: analog and digital. The analog sensor either complies to NTSC or

Table 8 Sensor decision matrix

Parameter	Parameter weight	Security camera		Gimbaled camera	
		Rating	Score	Rating	Score
Physical weight	15	4	60	1	15
Physical volume	15	3	45	2	30
Power consumption	10	4	40	2	20
Target resolution	25	3	75	4	100
Pointability	35	2	70	5	175
Total score			290		340

Phase Alternation Line (PAL) formats, with NTSC common in the USA and PAL common in Europe. An analog sensor requires an image capture board to convert the image stream to individual images in a common format such as Joint Photographic Experts Group (JPEG). Digital sensors provide an image that can be directly processed, usually in a raw format.

Each manufacturer of an EO sensor has specifications for their product, but the specifications don't provide sufficient information to determine whether or not the color quality will meet the project's image quality requirements. After defining the best candidates, sample cameras should be purchased so that image quality can be evaluated for the project's application.

5. Will the analog sensor generate GPS noise? Though a digital EO sensor should also be checked, NTSC analog sensors use a clock speed that has a harmonic at the GPS frequencies. This noise is further increased during the frame capture process. PAL EO sensors use a different frequency and do not generate the same noise.
6. Determine path between analog and digital signals.
7. Some digital EO sensors do not directly connect to a common computer bus such as USB or Ethernet; thus, a field programmable gate array interface must be used OnSemi (2015). Other complete sensors are available with either Ethernet or USB interfaces. When selecting a digital EO sensor for an application, in addition to image quality, ensure that computer connectivity meets your system requirements.
8. GPS EMI may be mitigated using a PAL versus NTSC sensor. If the UAV is large enough, separating the analog sensor and capture board from the GPS antenna may sufficiently mitigate the GPS interference. Noise can also be minimized by not using exposed camera or frame capture boards and carrying video signals between enclosures using shielded cables.
9. Most analog sensors interlace its image which means that it creates all odd lines in an image and then the even lines in an image. This can create jagged edges since the UAV is moving while the odd lines are captured followed by the capture of the even lines. The performance of edge detection algorithms is impacted by the jagged edges.

10. If multiple choices exist, select the best choice using WPV factors. Reduction in weight and power can either leave more allowance for other payload subsystems or increase flight time.
11. If no viable sensor can be found, new constraints must be negotiated with the customer.

Other considerations:

- If an analog sensor is used and images are transmitted to the ground station for processing, additional noise will be introduced from the analog wireless transmission.
- If a greater pan angle is required just for orbiting an object, mounting the sensor at an angle and then always orbiting in the direction that uses the desired tilt of the camera may eliminate the need for a more cumbersome gimbal system.

Power Subsystem

The power system includes batteries and DC-DC converters. Figure 10 shows the design flow (Fig. 10).

1. Define mission constraints.
   (a) Flight time will define the amount of battery capacity required for the mission. If extended operation of the payload is required on the ground before a UAV takes off, additional capacity is needed. A battery backup switch may be employed which allows an external battery to be connected while on the ground and then removed before takeoff. With a properly designed battery backup switch, the payload does not see a drop in voltage when the external battery is removed.
2. Payload constraints on the power system.
   (a) What is the weight allocation for the power system?
   (b) As subsystem designs evolve, are there additional power requirements identified?
3. While completing the subsystem design, verify the power budget using the technique presented in Table 1.
4. Nickel metal hydride (NiMH) and lithium polymer (Li-Po) batteries are the most common choices of battery technology in use for UAVs. Li-Po batteries have higher charge densities so are lighter than NiMH for the same stored energy. NiMH are less expensive than Li-Po batteries, but Li-Po batteries continue to come down in price. A key difference is in available voltages. The maximum NiMH pack voltage is 8.4 V, while Li-Po pack voltages are common to 18.5 V. The higher voltages provide better input to the DC-DC power supplies. Also, Li-Po batteries provide a more linear discharge for consistent power output. Special care must be taken with Li-Po technology to ensure that no overcharging occurs and that the batteries are not discharged to less than 3 V per cell.

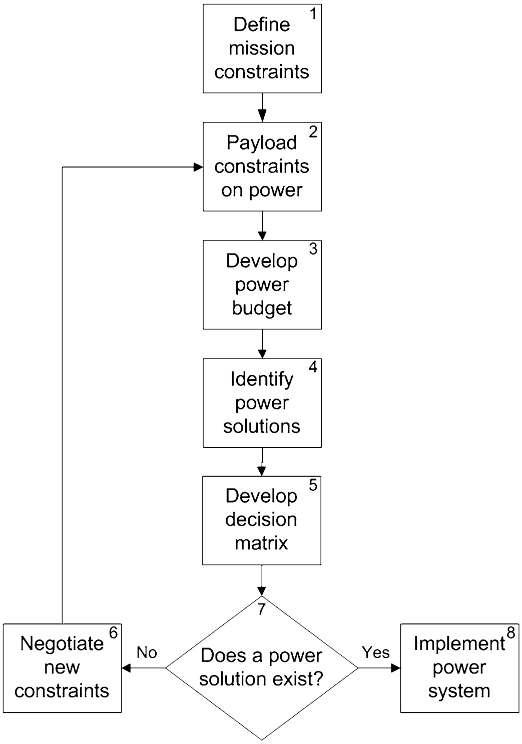

Fig. 10 Power subsystem design flow

DC-DC conversion is done with a switching power supply. DC-DC ATX supplies that have been developed for use in automobiles are a good choice. They can use a wide input voltage range and output 3.3-, 5-, and 12-DC voltages that are commonly used by computers, sensors, and communication systems.

5. A decision matrix may be employed as a tool to select the best power solution based on matrix's criteria.
6. If no viable power solution can be found, new constraints must be negotiated with the customer.
7. Decision box regarding existence of viable power solution.
8. Implement the selected power system, always recognizing opportunities to reduce weight and size wherever possible.

Other Payload Design Considerations

- Flight time restrictions: Most small UAV missions will be flown during good visibility and daylight hours so that the aircraft can always be observed in case of erratic behavior of the aircraft. Select sensors to optimize this time of day. Thermal sensors have difficulty identifying targets against warm backgrounds.

- Gas engines create greater vibration than electric motors. If a gas engine is required to increase the flight duration, place a vibration reduction mechanism at the engine instead of each of the payload subsystems.
- Autopilots and some thermal cameras fall under US International Traffic in Arms Regulations (ITAR). Even though you may not be shipping these items to foreign countries, they also cannot be used by foreign nationals located at the facility. Also, if any software that directly communicates with the drivers of these products is also ITAR controlled, it must comply with the same restrictions.
- An autopilot hardware in the loop (HIL) capability will greatly help in the development of control algorithms. The onboard computer can be directly connected to the autopilot, and the control software can be exercised using simulated flight.

Conclusion

In this chapter, payload design principles for small UAVs are presented. Using an example mission, we showed a design approach used at the US Air Force Academy Center for Unmanned Aircraft Systems Research and described solutions for a UAV system to meet mission requirements to perform autonomous ground target detection and tracking in support of an intelligence, surveillance, and reconnaissance operation. In detail, mission requirements; budget allocation for power, weight, and volume; and individual subsystem design are described with commercial hardware examples.

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