Waterloo Aerial Robotics Group
(WARG)

System Design of a UAV for Disaster Relief

Disaster Situation:

Train Wreck near a Remote Canadian Village

Student Unmanned Air System (UAS) Competition 2014 – 2015

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1 Mission Analysis

A train has derailed in a remote Canadian village and concerns have risen over the significant oil leakage coming from the wreckage. Exploding containers have demolished nearby buildings and caused substantial damage to portions of the town and surrounding area. The overlying problem is clear, and our team has been hired to evaluate the damage caused by the disaster in order to assess required clean-up efforts while also capturing evidence of the incident. The surrounding area must be surveyed, with any notable objects / areas of interest being identified. In order to provide the clients with critical data, the percentage of the field that has been contaminated must be calculated and mapped. A list of all structures that are located in the disaster area, with their corresponding level of damage, should be provided a long with their locations and an estimation of the volume of debris (individually calculated for each damaged structure). It is crucial that before any structures are assessed, the wounded / immobilized people must be located and their medical condition must be immediately assessed to allow emergency crews to make life saving decisions. This information can be provided in the form of a close-up photograph that includes a brief overview of the person's state, and their specific geolocation. After all of the above has been completed, the remaining container types are to be identified by reading the codes written on them, with their corresponding locations once again being provided to the client. All of the above information must be provided in a clear, concise, and professional report that will allow the client to make informed decisions as well as use the document in any future references to the disaster.

In order to successfully gather data on all desired aspects as outlined above, our aircraft must be capable of a few critical design requirements. The aircraft must be able to capture high resolution aerial images of the entire surveillance area, and the flight itself must be performed in an accurate, time-efficient, and safe manner over the area of interest. This means that the aircraft must have the necessary endurance to capture imagery of the entire surveillance area in a single flight without landing for refueling. Due to the state of emergency of the situation, the aircraft will more than likely be flying over emergency workers / volunteers as they are tending to the disaster. For this reason, the aircraft is required to have a flight termination system that can "kill" the aircraft should a reason to do so arise, and must also possess a takeoff weight of no more than 10kg. Once all of these requirements are met, the mission's success will be based off of the accuracy and correctness of the collected data.

2 Design Analysis

The described mission requires not only a UAV, but an entire system that must work together as a whole in order to complete the objectives at hand. Post-processing methods, although a crucial aspect of creating clear and informative data for the client, will not be discussed in great detail throughout this document. Instead, this document will focus on our team's ability to collect valuable and accurate data by presenting the decision making process that led to our final system. With this in mind, the following four core design criteria will be discussed: aircraft selection, autonomous capabilities, imagery, and real-time target acquisition / computer vision. Each of these four criteria significantly contributes to the mission's success. If any one of the criteria falls short of performing its role sufficiently, the UAV surveillance system as a whole will become susceptible to failure. A qualitative analysis of the design criteria has been performed, and this section of the report will summarize the findings.

2.1 Aircraft Selection

The selection of an aircraft affects many aspects both internal and external to the system. The aircraft's weight, flight endurance / fuel efficiency, and system vibration impact the system internally. On the other hand, the noise generated by the aircraft impacts the environment surrounding the UAV system (bystanders, wild life, etc.). Three types of aircraft were evaluated against these factors, to which a clear winner was found. A gas / glow engine (although either type is acceptable for this option, a gas / glow engine will be referred to as simply a glow engine from this point forward) based aircraft, electric battery powered aircraft, and solar based aircraft were compared against one another. Through qualitative analysis, the solar based aircraft can be immediately rejected since current technologies have not developed far enough to enable the aircraft to have sufficient flight endurance. If it were to be a cloudy day, the solar aircraft would be greatly hindered in terms of flight time. Evaluating the gas engine and electric aircraft against this same criteria, a small debate arises. Although a glow engine would be able to have longer flight times on a mass to fuel / energy basis, it could be said that the aircraft must only meet the provided flight time slot of 30 minutes. For this reason, although a glow engine is more energy efficient, both aircraft types meet the requirements. The glow engine aircraft has an advantage in terms of the aircraft's weight due to the fact that over the duration of the flight, the aircraft's weight is reduced as fuel is consumed. For an electric aircraft, the mass change of a battery is insignificant, and assuming an initial starting condition of similar masses of gas versus batteries, the gas aircraft wins. The factor which must be heavily weighted in the evaluation is that of system vibration, which can cause blurred images / video, and therefore potentially corrupt our datasets. It is commonly known that a glow engine struggles in this category, and mechanical vibration dampening must be researched and developed in order to counteract the engine. An electric based aircraft performs magnitudes better in this category, and vibrations caused by the propulsion system are greatly reduced in comparison to a glow engine. Following through in this category, this minimal vibration system also causes the electric based aircraft to produce less audible noise, making it a more environmentally friendly system.

2.2 Autonomous Capabilities

Although not a requirement of the system, a more autonomous aircraft will retrieve better data in a shorter amount of time. This is simply due to a human pilot's imperfections when trying to follow a determined path, or hold a set altitude from a far distance away. At a larger distance from the ground station, a well-tuned autopilot will be much more reliable than a human pilot. Path following accuracy is improved by magnitudes, and aircraft stabilization is also greatly enhanced. Both of these improvements in turn yield more accuracy of the collected data (imagery). When considering options between manual control versus a more autonomous solution, a well-developed autopilot will certainly be chosen. This can be further broken down by discussing the level of autonomy. Our team is looking to improve our aircraft by adding air speed and flaps / slats into the control algorithm. Although these additions can greatly enhance our autopilot capabilities, certain solutions may hinder our team more than they would benefit us. For example, developing autonomous takeoff / landing capabilities allows the autopilot to be completely self-sufficient. What must be considered is the time requirement of developing this technology. With the small window of time provided to our team, allocation of resources (member's time) may be better spent developing other portions of the system, rather than focusing on this somewhat unneeded feature. These solutions must be continually analyzed as our team proceeds through the development stage, but a clear decision can be made that a more autonomous aircraft will be more successful in the mission compared to a manually piloted aircraft.

2.3 Imagery

The prime data collected during flight is imagery, and because of this, various characteristics of the camera system greatly affect the path planning process. Taking into account image quality, desired ground resolution of the image, and focal length (angle of the image, where a wide angle captures more area but can distort the image more) we can calculate the optimal path to follow. The key to success is to fly as high as possible, while keeping quality and resolution of the captured images at a desirable level. Higher altitudes allow the aircraft to capture more ground area per image (assuming constant focal length), but at some point you begin to sacrifice image quality. From past experiences, our team believes that our selected altitude for flight is within an optimal range (between 100m to 120m), but we felt that the ground resolution seen in our captured images was less than desired. For this reason, we have decided to upgrade our camera system, specifically increasing resolution and relatively holding the same focal length properties as our current system. Our goal is to upgrade from a 12MP resolution, to 24MP. This is a significant improvement, and will provide us with more accurate results when performing calculations / post-processing on the targets in the images. We also face the challenge of reading barcodes that exist on the targets. To get clear information from these barcodes we may need to take close-up photographs. Our team has developed two viable solutions to this problem. We can purchase a camera lens with power-zoom capabilities, rather than a manually adjusted lens (or develop a mechanical fixture that physically zooms the lens). As an alternative, the camera could hold a constant focal length, and the aircraft could drop in altitude, take a photograph, and then once again climb to cruising altitude. Both solutions present benefits and complications, but only the camera lens option imposes a heavy cost impact on the budget.

2.4 Real-Time Target Acquisition / Computer Vision

To give our team an advantage against others, a real-time target acquisition system is being put in place to help manage the aircraft's path during flight (returning to crucial targets if required for a closer look). This system will also reduce post-processing times since we have already begun to identify targets during flight. In order to accomplish this, a video downlink will be established. This live video feed will be combined with telemetry data in order to geolocate targets. Two issues arise from this process that could greatly affect the efficiency and reliability of the system. These factors are the camera placement and target identification software. A forward facing camera provides the benefit of identifying targets before the aircraft (and main down facing camera) pass over the target area. This could allow us to plan for which targets we'd like to perform a "close-up" routine on, rather than having to return later on. Opposing this advantage is the possibility of collecting inaccurate geolocations of the targets due to the forward facing camera and more complex calculations / image distortions when locating the targets. A downward facing camera does not have the benefit of seeing targets approaching in the future, but in theory it provides the opportunity to collect more accurate data. Moving on from collecting the video, once the information arrives at the ground station, our team has the option to manually identify targets or use object recognition software. Both options come with their own pros and cons, so the solution may end up being a combination of the two. Object recognition can identify targets more accurately and quickly as they come onto the video feed, but depending on the algorithm, the reliability of identifying targets could be a huge issue. The benefit of manual detection is that a human can recognize targets that the object recognition may not have knowledge of. At the same time, a human will be slower, and potentially less accurate in identifying targets and geolocating them. In the end, the addition of any live target acquisition system will substantially improve our team's potential for success.

3 Final Design

It is crucial to consider the surveillance drone not simply as the UAV itself, but as an entire system that must work together as one in order to gather the desired data. This means that all communication, control, and tracking aspects of the system must work alongside the mechanical aircraft to successfully complete the mission. The system at an overview can be seen in *Figure 1* found in the appendix, which illustrates how various components of the surveillance system interact with one another, and what information each component relies on. Our team approached the design of this system by evaluating the alternatives described in the previous section, and adding several other design factors to help create a more robust system. The system design will be described starting with the aircraft itself, and working through the system down to the real-time target acquisition components. We believe that our team has designed a minimal system, where there are extremely few, or no aspects of the design that can be considered "fluff." What this means is that the team's schedule is crucial to meet and stay on track. Due to the minimal system design, every component is critical to the success of the mission, and removing a single component could severely hinder the UAV system.

The physical aircraft is not represented in the System Design Map, but is a crucial aspect of the system. An electric battery powered aircraft was selected for its capability to meet the desired flight time of 30 minutes, while also reducing any vibrations created by the propulsion system and minimizing noise generation. Furthermore, it was determined that an aircraft body would be purchased off-the-shelf rather than designed and built in-house. Due to the size of our system as shown in *Figure 1*, there already exists many tasks and components that need to be developed from the ground up. The addition of a mechanical aircraft body which may need further troubleshooting after its creation, only adds an unneeded level of complexity and yet another unknown. To substantially improve our team's potential for success, a styrofoam plane (specifically named the "Anaconda" on the market) was purchased and its internal frame may be modified to fit the needs of our team.

Moving on to the internals of the aircraft, our custom built autopilot (entitled the "PicPilot") manages the stabilization and path following capabilities of the UAV. By analyzing the data gathered through the sensors, the PicPilot has the potential to be fully autonomous from takeoff to landing. Our goal is to develop the most autonomous system possible, but due to time restrictions, some aspects may not be implemented in time. In this design, airspeed sensing has been added and opens up many opportunities regarding control of the aircraft. This data will allow us to utilize the flaps of the aircraft to perform time efficient "close-up" photographs of the targets. As well, knowing the airspeed of the aircraft we can perform fully autonomous takeoff and landing. Unfortunately, this capability is one that may be left out of the development phase if there seems to be limited time remaining. As previously stated, a more autonomous UAV in turn has more potential for success. The PicPilot must be capable of the following: full system orientation stabilization, accurate and smooth path following, accurately holding a desired altitude, and performing low-pass flights over selected targets. Additionally, the PicPilot must send telemetry / other data to the ground through the downlink as well as control, or interact with the controllers of, the camera gimbals to ensure stable and clear video / imagery. The PicpIlot will also control when an image is captured by the main camera. On board the aircraft is also the video downlink system, which provides the ground station with a live video feed from the UAV camera. All of these systems make up what is known as the UAV, and provides our ground control station with the necessary information to make decisions, while also collecting accurate and precise data.

Signal reliability can be the success, or failure point of a UAV system. If the telemetry / data link is lost, we can no longer control the aircraft and flight termination must occur. If the pilot's control uplink is lost, manual flight control is lost and no recovery measures can be taken if the autopilot malfunctions. If the video downlink is lost, targets cannot be identified in real-time and therefore crucial images may not be taken. Due to the three or four signals existing on the aircraft (pilot control and the video link can potentially be combined into one), the UAV becomes even more susceptible to signal interference / corruption. The tracking antenna was designed to battle this exact problem. With the use of Yagi antennas our team hopes to obtain more reliable connections with the UAV. Although signal interference is still a possibility, the Yagi antennas and tracking system should ensure a strong connection at a large distance. All three signals exist in completely separate spectrums, meaning that in theory they should not interfere with one another. The tracking antenna system as a whole is responsible for collecting information from the UAV and providing it to the systems that require such information, as well as sending information to the UAV. This network must be as robust and reliable as the signal connections, since many essential systems retrieve critical information from this network. Overall, the tracking antenna system is the team's life line for information distribution.

The ground station must be capable of monitoring and control of the UAV, as well as identifying targets in real-time. The ground control station (GCS) must be capable of manipulating the UAV's flight and changing flight paths on the fly. This station will receive the location of targets as the target acquisition systems identify them. With this information, the GCS operator can make any flight path modifications they see fit, and identify locations that the UAV should perform low-pass moments of flight. The target acquisition software will be both human and software operated. To reduce the risk of missing targets, while also improving accuracy of target geolocations, a human operator will work alongside object recognition software. Combining the benefits of a human operator and software identification significantly improves the reliability of the target acquisition system. Once a target is identified, the coordinates and target type is relayed to the GCS and the Acquired Targets Monitor. This monitor is simply a large map of the disaster area, with identified target locations being continuously updated. This system provides team members with up-to-date information that can be crucial to the decision making process on the day of the mission. As a unit, the components of the ground station collect information from the UAV and process the data, allowing team members to make real-time decisions and modify aspects of the flight as desired.

As previously stated, the image / post-processing system will not be described in great detail. As an overview, this system must be capable of: more accurately geolocating targets by means of the high resolution images, finding the area / volume of the applicable targets, identifying the state of targets by visual means (level of damage, medical state of a person, etc.), identify targets by means of analyzing barcodes, and creating a map of the entire area of interest. Our team has acquired software capable of finding the volume (or height) of an object from a set of images, as well as creating a large image mosaic. This software will be used in order to reduce development tasks, and therefore free up resources (member's time) to develop the other components shown in *Figure 1*. Our team will be responsible for the geolocation, identification (both visual and barcode based), and area calculation of necessary targets. It is our goal to create a post-processing system that will automatically create a clear, concise report for the client.

4 Radio Frequency

The following is a list of radio frequencies that our team will be using through the mission, along with their respective transmission power level:

- 433MHz (up to 600mW) – Pilot Control of Aircraft (*More than likely will be eliminated)
- 900MHz (250mW) – Telemetry / GCS Control of Aircraft
- 2.4GHz (100mW) – Video Downlink (*This system can also accept pilot control of the aircraft)

These frequencies will be operational by our aircraft throughout the duration of the flight. On completion, the frequencies above will be terminated, and no further transmissions will occur.

5 Novel Features

Our system possess a few key features that ensure our team's success over others. The real-time target acquisition system (including the video downlink) enables our team to make flight modifications based on target locations. Normally, target placement would not be identified until after the UAV has landed and the images have been gathered. The video downlink allows us to identify targets immediately during flight, and utilize that information appropriately. Another key enhancement is the tracking antenna system, which ensures a strong signal connection to the UAV. Previously, as the aircraft flew farther and farther away from the ground station, the signal to the UAV began to cut out. The tracking antenna addresses this issue, and ensures that the ground station is always in contact with the UAV. None of these features are useful unless there is a UAV to communicate with, and for this reason, although not the most novel feature, the autopilot is the most important. Our fully autonomous UAV removes human error and imprecision from the system, ensuring a smooth flight throughout the mission.

The features listed above effect the ability to collect the data, but only slightly effect the quality of the data. As another key feature of our system, our fast focusing 24MP Sony A6000 camera is a substantial improvement. This upgrade to the camera system allows the UAV to fly at high altitudes, while still improving ground resolution. Higher ground resolutions in the captured images means that the geolocation, area, and volume of targets will be more precise. As well, barcodes can be read at a greater distance from the targets. The selected camera is yet another novel feature of our system that gives us an advantage over other teams.

6 Scheduling and Risk Management

The project shall proceed through various stages of its design phase, while continuously checking the probability of its success during any given stage. This includes many sessions of real life testing, where the aircraft, or other components, are vigorously tested to ensure that they work under all relevant conditions. This process is how our team minimizes the risk of project failure. In order to ensure that the team has a working product in the end that will successfully complete the task for the client, we test the aircraft on multiple occasions to verify that it can in fact successfully accomplish the mission. Our team believes that an aircraft that has been thoroughly designed, with every little aspect or detail thought of for weeks at a time, does not necessarily ensure its success. On the other hand, an aircraft that has been continuously tested provides reasoning for its failures as the test flights progress. Since these failures are found earlier in the design phase, they can be addressed and modified to create a working product.

Therefore, as previously stated, risk is drastically reduced by our team through vigorous testing, where the aircraft is able to successfully complete the mission without fault. This is simply due to the fact that all of the faults have been found through testing, and corrected appropriately.

In terms of direct risk to the system, there is one system that has the opportunity to become a single point failure, and needs to be thoroughly tested to ensure reliability. If we assume that all components of the design are developed properly, and work as desired, the tracking antenna system becomes the most critical component of the system for ensuring success of the mission. If communication with the UAV is lost by any of the three components relying on their respective signal, catastrophic failure has the potential of occurring. For example, if the autopilot fails for some unforeseen reason, the pilot must still have his manual control connection in order to recover the UAV to stable flight. If telemetry is lost from the aircraft, our team can no longer monitor and control the UAV. Furthermore, if the UAV is far away from the ground station (where the pilot exists) and telemetry is lost, the potential for recovery of the UAV is significantly reduced. At that point, system recovery solely relies on the autopilot's ability to bring the UAV back to the ground station, where hopefully the pilot will still have manual control and can land the aircraft safely. Signal reliability is a clear single point of failure to the system, and must be tested vigorously to ensure mission success.

In order to accomplish the testing described above, the team wishes to have its final product complete two months prior to the designated flight date. This will provide the team with enough time to address any issues that arise in the final system, and ensure that the aircraft is successfully able to complete the mission for the client. Various aspects of the design phase are already coming to an end, and the team is working to build, and finalize these prototypes into a fully capable UAV. On the day of the mission, we are positive that our scheduling and risk assessment will help us prevail where other teams might fail.

7 UAS Performance and Safety

As addressed in the section entitled *Scheduling and Risk Management*, the team will be testing the aircraft throughout various stages in its design process. The performance of the UAS will be evaluated at each of these stages, and modified if the test does not meet the team's standards. It is our goal that the aircraft is able to complete its task without fail, and therefore the performance of the aircraft (or other components) during the designated tests is crucial to the project's overall success. The aircraft has currently been through multiple test flights in its prototype stage, and has successfully flown with controlled flight techniques built in to the autopilot. The aircraft is progressing with these tests, and each test improves the aircraft's capabilities. The performance of the aircraft is monitored through each stage, but will not progress to the next stage of testing until it has met the team's standards. This method reassures our clients that the final product is capable of completing the required mission.

Although it is critical that the aircraft is able to complete the task given to our team, it is key to note that safety is always crucial to our aircraft's success. A few concerns may arise due to the aircraft's electric propulsion system with regards to battery life. This concern is addressed by isolating various components onto their own power supply. This means that all components are run off of their own battery, which helps ensure that the pilot will have full control over the aircraft should anything happen during flight. These components include (but are not limited to): the autopilot, propulsion system, and receiver. It is key to note that the pilot possesses the ability to take over control of the aircraft at any point during its flight. Included in the autopilot is a hardware bypass system that allows the pilot to send direct signals to the aircraft's control interfaces, and lock out any signals from the autopilot. This feature is key to ensuring safety during the aircraft's flight, providing a fast and efficient way to take control of the aircraft if necessary.

To ensure the mission can be safely completed, the aircraft will be tested to ensure all of its safety features work time and time again. The team will test the aircraft past its furthest point of flight as calculated based on the designated surveillance area provided (approximately 2km). Performing this test will ensure that the pilot can regain control of the aircraft should it proceed outside of the designated boundaries. The aircraft will also be tested to mimic battery failure in flight. This test will provide excellent data for ensuring that the aircraft can still operate if any of the power supplies fail, and that it can safely return to a designated base location. The safety features of the aircraft described above are of high priority to the team, and testing the reliance of each feature allows all parties to gain better insight to the safety of our aircraft.

The following is a list of safety features that will be built into the aircraft, and followed to ensure safety:

- Lost Communication: If communication is lost with the UAV, it should return home after 10 seconds. If communication is not reacquired after 2 minutes, flight must be terminated.
- RC Uplink Failure: In case of RC uplink failure, the team captain should notify the Air Program Director. No immediate action is required. The kill switch should still be working at this time.
- Lost GPS: If GPS is lost, alternate manual and controlled navigation of the UAV should be retaken (i.e. FPV). Otherwise, flight must be terminated.
- Outside Mission Boundary: In case the UAV gets outside the mission boundaries, the Air Program Director should be immediately informed. No immediate action is required but the Air Program Director may ask to terminate flight, which would mean near vertical descent must be achieved (aerodynamic termination).
- Lost Communication AND Outside Mission Boundary: If the UAV loses communication AND is outside the mission boundary, flight must be terminated.

8 Budget

Our team has projected that the aircraft, and all of its subcomponents that make up the system, will cost approximately $9'500. This value includes travel (transportation and accommodations) and sponsor advertisement (t-shirts, banners, etc.), which may not directly contribute to the UAV system, but do in fact contribute to cost and budget. *Table 1* is a brief list of both estimated and calculated values that have been researched throughout the design process of the aircraft. The budget has been summarized into several categories as shown in order to provide the information in a more reasonable manner. Note that the budget, as shown, is subject to change depending on design changes and the costs shown are of an anticipated value.

Sub-Project	Anticipated Cost
Camera System	$3’460
Tracking Antenna	$870
Aircraft	$1’650
Post-Processing Computer System	$1000
Travel	$2000
Sponsorship	$510
Total Anticipated Cost	***$9’490***

Table 1 – Anticipated Budget

It is crucial to note that the team is currently contacting sponsors regarding various components of the aircraft, and has already received various donations that will drastically reduce costs of the project. An autopilot board has already been provided to the team by a significant member, which dramatically reduces purchasing costs of the system. This autopilot board was received with partial hardware components completed, but the control code did not exist. Therefore, the team is in the process of creating our own control code for the aircraft, and hence the aircraft’s autonomous capabilities will be designed solely by the team. It is also key to note that the team possesses many past projects that currently reside in storage. The team is looking to recycle various components of these aircraft to gain further use of items purchased in the past.

9 Conclusion

The proposed mission will be resolved by using the system that has been discussed throughout this document. The mission will begin once the aircraft has taken off from the runway, and proceeded towards the designated area of interest. From here, the aircraft will then begin to follow a pre-determined path to thoroughly search every aspect of the area. As the plane progresses through its flight, a camera will capture photographs of the terrain below at precise locations that will be calculated to ensure the photographs taken cover the area in its entirety, as well as contain image overlap. Once the entire area has been searched, the aircraft will return back to base and land using the runway provided. The SD card of the main camera will then be retrieved from the aircraft, which has all of the mission images saved to it. These images will also include metadata related to the photographs location (latitude, longitude, altitude, heading, etc.), which will allow the team to stitch the images together and create a map of the surveyed area. The software that creates the image mosaic will also be used to find the volume of selected targets after the mosaic has been completed. In parallel to this process, our team will be identifying target characteristics and finding their geolocations using software developed in-house. After completing the above tasks, the team will create a report outlining all of the necessary data that the client has asked for. The report will then be handed to supervising personnel for review, and the mission will be concluded.

Appendix

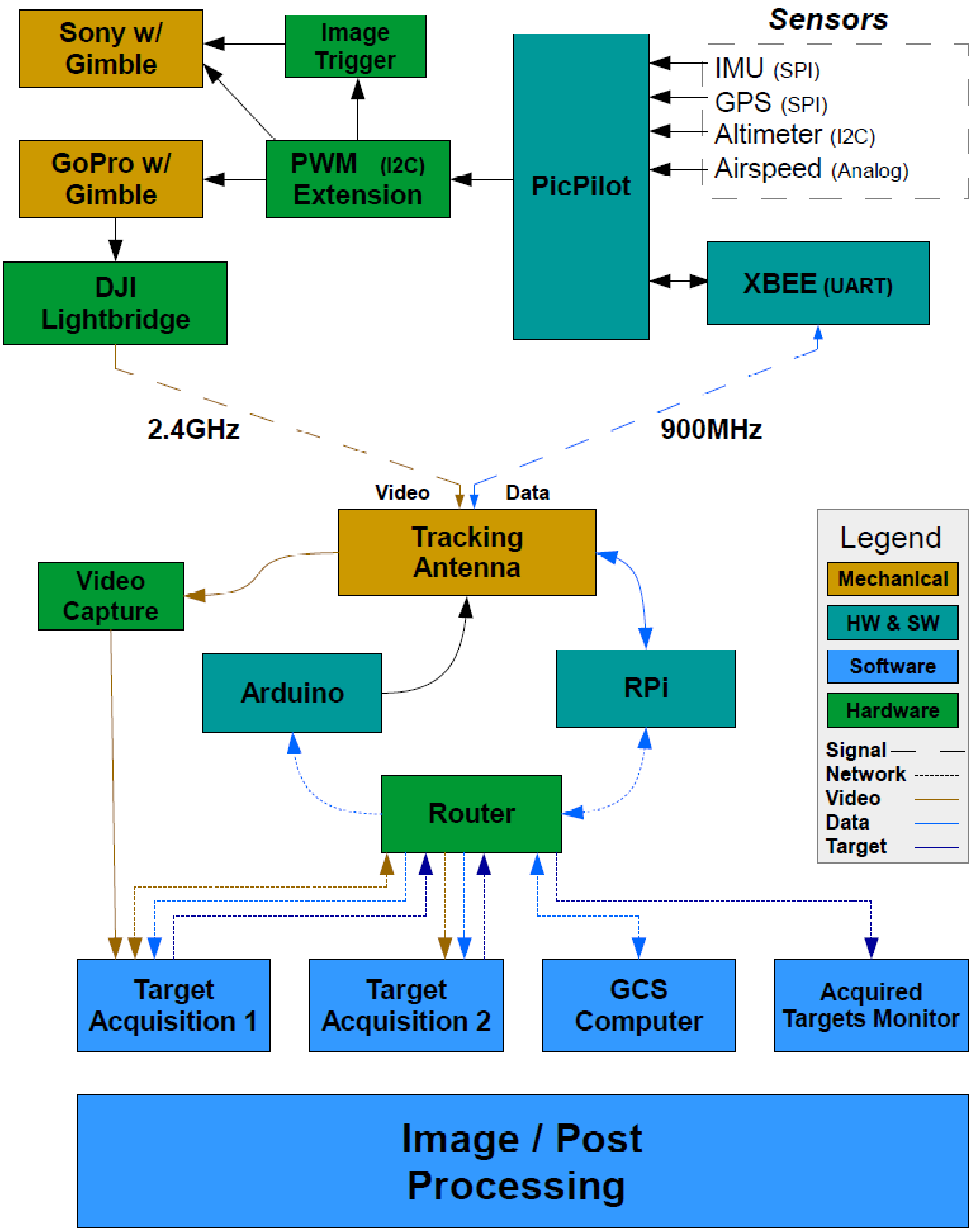

Figure 1 – WARG UAV System Design Map