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## A Modular Onboard Processing System for Small Unmanned Vehicles

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A Modular Onboard Processing System for  
Small Unmanned Vehicles

by

Richard D. Garcia

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science in Computer Science  
Department of Computer Science and Engineering  
College of Engineering  
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ABSTRACT

This work describes the design and implementation of a generic lightweight onboard processing system for miniature Unmanned Vehicles (UVs) that is computationally powerful and highly adaptable. First, several classical approaches to giant scale and full size UV onboard processing systems are described along with their corresponding limitations. Second, a detailed study is presented that describes the key characteristics of an onboard system along with associated limitations. Next, an implementation of a generic onboard system capable of vision processing and servo based control is presented along with detailed hardware specifications and implementation software. Last, experimental data, both laboratory and field, are presented to show validation of the onboard processing system design, functionality, and key characteristics presented.

Two primary contributions are made in this work. i) Identification of key characteristics of an onboard system allows for a high level validation of the hardware of an onboard system along with a design template for a reconfigurable, platform independent, processing system for UVs. ii) Detailed design and implementation of an adaptable onboard processing system that is both computationally powerful and easily adapted.

This system is validated by showing satisfiability of the design characteristics necessary for an adaptable onboard system along with fully operational field test and their corresponding results.



## Chapter 1

### Introduction

#### 1.1 Introduction & Motivation

The goal of this thesis is to provide a high powered onboard system capable of running online vision algorithms and feedback control from multiple unmanned platforms including miniature ones. This processing system's nonspecific nature allows for simple "plug and play" of the system onto platforms including, but not necessary limited to, both aerial and ground vehicles. This work is relevant not only to robotics but to any reconnaissance type platform that must be functional regardless of communication status. This chapter presents both the research question and the motivation behind the work. The last section of this chapter details the contributions of this work and outlines the specific areas of this thesis that support these claims.

The research is motivated by the challenge to design, implement, and test an on-board processing system that is capable of computationally expensive algorithms regardless of ground station connection yet is nonspecific enough to function on multiple platform vehicles tasked with very distinct goals. This thesis focuses specifically on miniature ground and aerial vehicles whose characteristics typically include a small foot print, low endurance, and minimal payload capacity. Although the focus is on miniature vehicles the validity of the processing system is not limited to these platforms.

Fundamental issues justifying implementation of an onboard processing system as opposed to ground station processing are three fold:

- Reduce the overall network traffic
- Increase the quality of data processing
- Increase the vehicles level autonomy

## 1.2 Problem Statement

The problem the thesis addresses is as follows:

Miniature unmanned vehicles are becoming popular due to their compact size, high maneuverability and high size-to payload ratio. This is especially true with Vertical Takeoff and Landing (VTOL) vehicles due to their distinct capabilities to maneuver in any direction and to hover, even in highly confined areas. Efficiency and functionality are the main goals of any unmanned vehicle. In vehicles specifically designed for quick and easy deployment, it is imperative that any onboard equipment be as generic and adaptable as possible. This creates an environment where resources can be stretched further without jeopardizing response time or effectiveness. This statement has served as the reference point for the proposed onboard processing system.

Payload is, without question, the most limiting factor in miniature UV platforms. It is also the main boundary between larger UV platforms and miniature UV platforms. Larger UV platforms are capable of carrying large generators and sacrificing horse power for electrical power. This allows onboard system development with very little regard to electrical needs of the system. This is not the case in miniature UV platforms. Miniature platforms can sacrifice neither the horsepower nor the payload loss required to generate electrical power. Experiments, presented in Chapter 6, show realistic payload limitations of approximately 8.5 pounds for a typical miniature UV platform. This creates major restrictions on the devices that can be placed on the platform. For these reasons it is typical to see many miniature UVs equipped with only lightweight cameras and transmitters that convey their information to ground stations. The transmitted data is then used by ground processing systems to perform all the necessary computations.

These types of ground processing systems contain a serious bottleneck. The data transmission via wireless communication channels introduces both noise and data loss [1]. The transmitted video is commonly littered with static and color rearrangements, as visible in Figure 1. It is also typical to see complete video dropout due to lost communication or bandwidth limitations. Wireless transmission also entails serious security issues. Transmitted data may be maliciously damaged or stolen. Software encryption only adds to the computational demands of the ground processing system and hardware encryption only taxes the already limited payload of the platform.

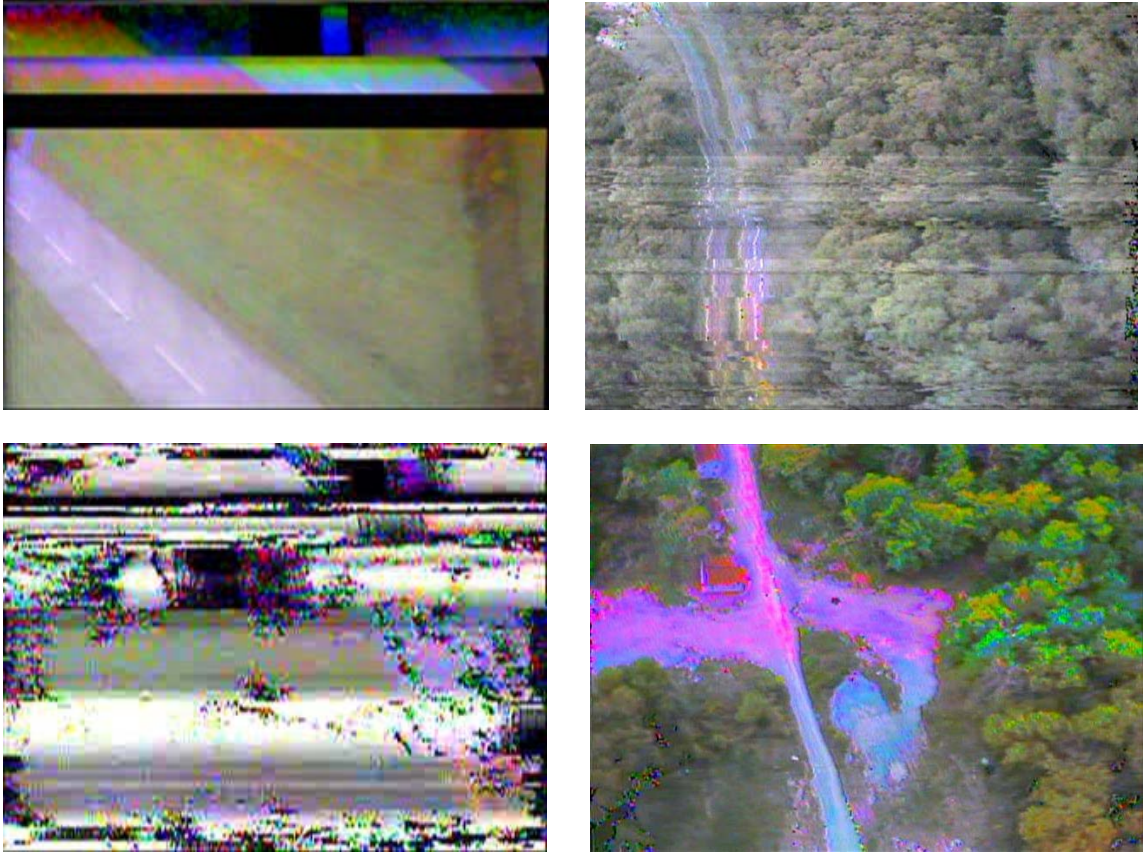


Figure 1: Examples of Wireless Video Noise Taken from a UAV

### 1.3 Proposed Solution

The proposed solution presented in this thesis is a generic lightweight onboard system capable of computationally high algorithms, is highly adaptable, has low power requirements, and is physically durable. This is first accomplished by identifying generic requirements that the onboard system must adhere to including payload, power usage, heat emissions, communications, etc.

To meet the onboard system's requirements for adaptability, weight, heat emissions, and power usage an ITX embedded motherboard capable of 1.2 GHz was chosen. This allowed the onboard system to utilize a multitude of I/O ports including up to one gigabyte of Random Access Memory (RAM) and two Integrated Drive Electronics (IDE) devices in a single board with a small footprint (6.7"x6.7"). To adhere to data typically required on UV platforms the onboard system was outfitted with one gigabyte non-volatile memory (compact flash), a Global

Positioning System (GPS) receiver, wireless communication (802.11B), a camera (Unibrain Fire-I), and a Pulse Width Modulation (PWM) controller capable of controlling up to eight distinct devices.

To further advance the onboard system's adaptability it was loaded with a highly developed and adaptable non-graphical operating system (Slackware Linux 10.0 with a 2.4.26 kernel). This allows the onboard system plug and play capabilities and access to commercial and open source software while requiring less than 100 megabytes of non-volatile memory.

Last, the onboard system is mounted within a shock resistant enclosure that is resilient to liquid vapors and debris while remaining extremely lightweight. This allows the system functionality in varying and unknown physical situations without limiting the abilities of the system.

#### 1.4 Thesis Outline

The remainder of this thesis is organized as follows. Chapter Two provides an overview of related work along with corresponding limitations, while Chapter Three presents a list of generic abilities for onboard systems along with justifications. Chapter Four and Five describe, in detail, the proposed solution including the utilized hardware and software respectively along with justifications for both. Chapter Six is dedicated to detailed descriptions of performed experiments including results. Chapter Seven concludes this thesis with a closing discussion and is followed by References.

## Chapter 2

### Related Work

There is currently great interest in designing on-board easily reconfigurable systems for miniature UVs. Although miniature on-board systems are a fairly new area of research, there has been extensive research into full size [37, 33] and giant scale [23, 2] systems, especially in the area of on-board vision processing [7], see Tables 2 & 3 in the Appendix. Full size and giant scale UVs correspond to vehicles proportional in size to their manned counterparts and vehicles that require special permission, typically Federal Aviation Administration (FAA) clearance, to operate (i.e. >55 lb model aircraft), respectively.

#### 2.1 Full Size Onboard Systems

One example of a full size onboard system is the one present on the Georgia Institute of Technology's teleautonomous High Mobility Multi-Purpose Wheeled Vehicle (HMMWV). This system, developed in 1997 under the guidance of Dr. Ronald Arkin, is capable of semi-autonomous and teleoperated navigation [5]. The system was developed on a military type 4x4 HMMWV vehicle, as seen in Figure 2, and supported a combination of on-board and off-board processing.

The Georgia Tech HMMWV was equipped with a GPS receiver, onboard gyro stabilized Inertial Measurement Unit (IMU), and a radio modem for ground communication. The onboard system was further equipped with three actuators responsible for controlling steering, braking, and throttle. The onboard system is completed with two PC-104 stacks responsible for low level control of the actuators, communication, and heading determination. The entire system is powered by the HMMWV's standard alternator which is inverted to 110 Volts Alternating Current (VAC).

Although this design allows a remote operator to successfully navigate the Unmanned Ground Vehicle (UGV) to a determined location, it is not without faults. The most serious issue with this type of onboard system is its design around a large non-commercial platform. The

system utilizes large actuators that are designed to run off of the platform's standard battery supply, 24V [5]. This onboard system would require redesign of the actuator equipment to be implemented on the majority of commercial vehicles which operate at half the voltage and amperage as the HMMWV. This design also requires communication to be present at all times to function correctly. This is due to the design's partial control and processing from an off-board system.

More current full size onboard systems in development include the Spartan Scout Unmanned Surface Vehicle as seen in Figure 2. The Spartan is a rigid hull inflatable boat capable of semi-autonomous control. It varies around 7 meters in length and is capable of carrying payloads up to 3,200 lbs at ranges up to 14 miles for 3 hours [37, 28]. The Spartan Scout is controlled via a Graphical User Interface (GUI) from a nearby parent vessel.

The basic onboard equipment contained on the Spartan Scout is an electro-optical/infrared surveillance turret, surface radar, digital imagery transmission system, and an unmanned command and control system [30]. This equipment is standard on all Spartan vehicles and allows the onboard system a concrete base of hardware to work with. This vessel is designed to integrate a multitude of modular pods allowing the platform to be quickly and easily customized for a specific task. The Spartan's modular pods include devices for Reconnaissance, Surveillance, and Target Acquisition (RSTA), Precision Strike (PS), Anti-Surface Warfare (ASuW), Force Protection (FP), and littoral Mine Warfare (MIW) [19].

Although the Spartan allows large manned naval vessels to extend the range of their sensors and counter enemy attacks with minimal risk, it does come at a price: approximately \$30 million United States Dollars (USD) for the development of four prototypes [37]. This price tag presents a serious limitation in the non-military areas of research. This onboard system is also not well designed to function on smaller UVs due to system's use of a large environmentally enclosed surveillance turret and surface radar which are both physically large and typically have high power consumption.

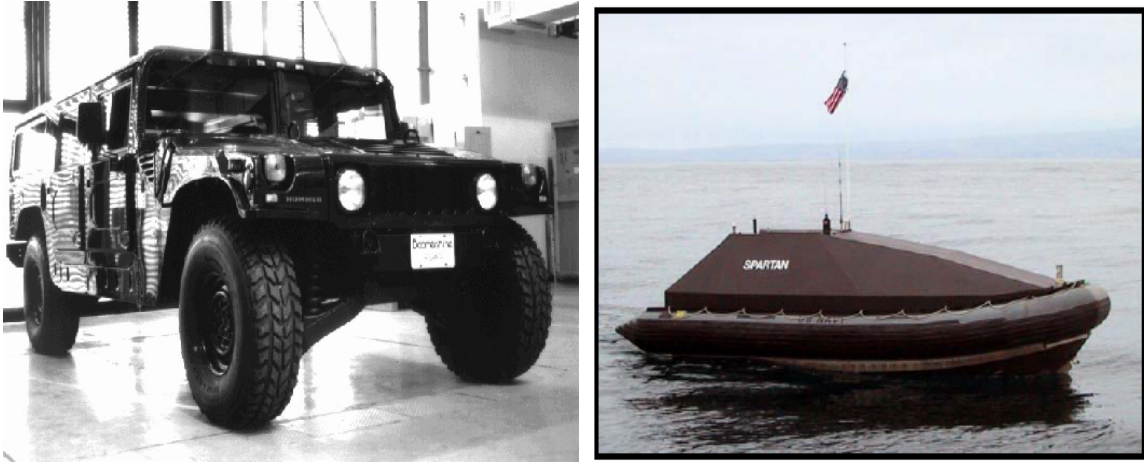


Figure 2: Georgia Tech Teleautonomous HMMWV and U.S. Navy Spartan Scout

## 2.2 Giant Scale Onboard Systems

One example of a giant scale onboard system is the one present on the Mobile Detection Assessment Response System – Exterior (MDARS-E). This is a jeep style platform that is designed to fit within the bed of a large commercial truck or the back of a HMMVW. It was designed to complete security tasks, intruder detection, and respond to alarms and is a joint Army-Navy development effort [35]. It is built around a four wheel frame which utilizes an all-terrain suspension, hydraulic steering and is capable of speeds up to 40 Mph [36].

The MDARS-E is equipped to navigate outdoor terrain by use of differential GPS and vehicle dead reckoning which are fused during movement to provide an accurate position. The onboard system is also capable of obstacle avoidance through the use of four types of onboard sensors: millimeter wave radar, stereo vision range finders, a single point scanning laser, and multiple ultrasonic sensors. Intrusion detection is accomplished using a narrow Field of View (FOV) radar, Forward-Looking Infrared (FLIR), and passive infrared sensors all mounted to a turret capable of 360° of movement [34].

The MDARS-E's hardware paired with advanced vision recognition software and communications allows for a very robust autonomous, semi-autonomous, and teleoperated vehicle. One distinct disadvantage of this type of design is cost which can exceed \$500,000 USD. A second limitation to the MDARS-E UV is power consumption. The functionality of the vehicle relies on multiple panning and tilting units that utilize several active sensors including



radar, laser, and ultra sonic. These types of sensors are also typically heavy in weight and have a high power consumption rate.

Giant scale aircraft have also proven to be extremely effective platforms for on-board processing systems. One particularly notable platform is the Yamaha RMAX. This platform consists of a 2-stroke horizontally opposed 246cc engine mounted to a 3.63 m long frame [29]. The platform has a payload capacity of approximately 28 kg which allows it to accommodate very large onboard systems containing multiple cameras, a radar altimeter, and complete desktop size computer [17]. The most notable usage of the Yamaha RMAX is Georgia Tech's GMAX.

Georgia Tech's Software Enabled Control (SEC) has used the RMAX platform along with a custom developed onboard system to assist in high performance autonomous control of the unmanned aerial vehicle (UAV) VTOL, see Figure 3. Georgia Tech's onboard system consist of a NovAtel RT-2 GPS receiver, sonar altimeter, HMR-2300 Magnetometer, ISIS-IMU, Radar Altimeter, two onboard computers, and an Aironet MC4800 wireless data unit [17]. The entire onboard system is powered by the RMAX's onboard generator and control of the helicopter is handled by both Georgia Tech's onboard system and the Yamaha Attitude Control System (YACS) present on all standard RMAX vehicles.



Figure 3: Giant Scale UAV (GTMax)

The GT-MAX with its high payload capabilities, extensive sensor suites, auto stabilization, flight guidance software, and long endurance rank it as one of they top autonomous UAV VTOL's in the world. Although the system is highly advanced and developed it is not without issues. First, the RMAX platform is nine feet long from tail to nose without the blades attached and weighs in at approximately 140 lbs. The sheer size and weight of the vehicle and



hardware limits its transportation to oversized ground freight and specialized air transport. This makes efficient deployment of this type of vehicle very difficult. Second, the RMAX platform with the GPS option and a 100 meter flight ceiling has a price tag of approximately \$240,000 USD. This is without the custom flight control system, IMU, ground radar, vision system, and support equipment. Last, the RMAX platform does not contain an autorotation clutch. This device, installed on all modern full-size VTOL aircraft, allows the platform to maneuver in the event of an engine failure. It is fairly trivial for a trained pilot to safely fly and land a VTOL vehicle containing an autorotation clutch that has had engine failure. This is a serious safety issue and should be considered when utilizing a VTOL vehicle without an autorotation clutch.

### 2.3 Midsize Onboard Systems

Midsize UVs are the most common and frequently used unmanned platforms today. Midsize vehicles are capable of long run times, reasonable payload capacities, and somewhat simplified storage and deployment. Above all, midsize platforms are popular due to their relatively inexpensive cost ranging from several thousand dollars to a few hundred thousand. This is mainly due to the platforms ability to function using highly manufactured parts that do not require modification for size, weight and power consumption.

Although onboard processing for midsize UGVs is a fairly well researched area there has recently been a great deal of interest in on-board processing for midsize UAVs. Most notable among these size platforms is USC's Autonomous Vehicle Aerial Tracking and Reconnaissance (AVATAR) vehicle which incorporates three firewire cameras, two IMUs, two PC-104 stacks (a stack of 5 and 6), two wireless transmitters, two solid state drives, and two power supplies [38]. This onboard system is mounted on a Bergen Industrial Twin helicopter utilizing a 46cc twin cylinder two cycle engine with a 10 kg payload capacity.

The AVATAR vehicle has been shown to be effective in both autonomous flight and visual identification of objects [21]. The AVATAR has also combined its visual recognition abilities with its flight capabilities to perform vision assisted flight. This ability has been used to accomplish vision based autonomous landings and the tracking of objects of interest. The AVATAR has also been used in the deployment of marsupial robots and the autonomous deployment and repair of sensor networks [10].

AVATAR, like its giant scale counterparts, is still plagued with deployment and storage issues. The stock Industrial Twin platform is almost 5 feet long and 2 feet high without blades or

modified skids. This limits this design to freight and specialized air transport making fast deployment very difficult and expensive. Another drawback to the AVATAR onboard system is its development around 11 PC-104 boards in two stacks. This type of configuration forces the onboard system into rectangular masses. This design's hardware choices limit the mounting capability of the onboard system which, on aerial vehicles, is typically already limited by flight characteristics of the platform. This also imposes serious problems when one considering moving the setup to another platform.

## 2.4 Adaptable Onboard Systems

There has also been considerable research into the area of “plug and play” sensor suites that connect to highly adaptable onboard systems [20]. These adaptable onboard systems allow sensor suites, typically referred to as sensor/module pods, which are typically highly specialized, to easily interface with the onboard system and vehicle platform. These modular pods are present on a multitude of vehicles including the previously mentioned SPARTAN Scout. They are typically low profile devices utilizing universal mounts for sensor pods that, in aircraft, are typically mounted directly below the fuselage and transmit information to the onboard system and/or ground station. These complex and highly developed devices allow a single platform to function for multiple tasks with only the replacement of a single pod required.

## 2.5 Summary

Although prior research has shown the enormous benefits of onboard processing systems specifically to highly adaptable and highly mobile platforms, the migration of these systems to small highly agile platforms has yet to be fully explored. To effectively utilize the many benefits of miniature UVs, onboard processing, comparable to those of larger platforms, must be developed.

## Chapter 3

### Onboard System Development

Although the idea of onboard system processing for miniature UVs appears to be a fairly straight forward design and implementation process, it does have several unforeseen pitfalls that must be explored before an effective and efficient design can be accomplished. First, a designer of an adaptable onboard system must identify generic abilities that are very typical to the functional areas of the system. The designer must then consider the limitations of the platforms and hardware, including issues related to payload limitations, platform propulsion, platform limitations, operating environment, system power, and safety, all of which increase the complexity of onboard system design. Specific details of the hardware utilized in validation of this system are described in Chapter 4.

#### 3.1 Generic Abilities

Adaptable systems must be generic enough to allow for functionality over a large domain but refrain from forcing the user into using hardware that may be un-useful or even hazardous to a task. To accomplish this, one must first identify and research the area of functionality of the adaptable system. In the case of UV's one must familiarize themselves with known UV platforms and the type of tasks they are required to perform and identify common aspects of these tasks.

##### 3.1.1 Position

Positional awareness is one of the most important aspects that a UV must handle. Whether a UV is designed for indoor and/or outdoor environments it must have some idea of its position with respect to its environment. This can be accomplished in many ways some of which include, landmark based localization, dead reckoning, integration of velocity or acceleration, and

GPS. Although each method has its benefits they all attempt to accurately calculate the current, past, and future positions of a UV.

Of all the methods for calculating position GPS is the most widely utilized. It allows a UV positional data in three dimensions with reference to the earth's coordinate system. This allows for robust and precise positional accuracy in most of the world. Although GPS is fairly robust it does have several issues, it cannot function indoors without use of specially placed GPS repeaters and it must have a fairly unobstructed view of the sky for accurate position calculation. Positional data via GPS can even be corrupted by heavy cloud cover. Although GPS does have flaws it continues to be the most widely used method for outdoor position calculation.

For robustness, an adaptable system must also be able to function in areas where GPS is not a realistic option: indoor environments and near buildings or large obstacles. This is the rationale for vision based localization, dead reckoning, and integration of velocity or acceleration which gives position with respect to the UV. Although these techniques are fairly inadequate by themselves combinations of them have proven to be very effective [11].

To allow for positional accuracy both indoors and outdoors it was decided that the onboard processing system be equipped with both vision and GPS capabilities. For both the above reasons and reasoning to be mentioned in the following sections it was determined that the adaptable system be equipped with accelerometers on 3 axes. These three sensors allow the system to function outdoors with positional accuracy provided by GPS, indoors with positional accuracy provided by both the camera and accelerometers, and in transitions from both outdoor and indoor provided by all three sensors.

### 3.1.2 Orientation

Orientation also plays a vital role in most UV designs. Position can provide information about the current state of the UV but is insufficient when the vehicle attempts to transition to a new position. Typical platforms such as fixed wing planes, VTOLs, Ackermann and skid steering vehicles all require heading (yaw) to transition from a current position to a desired position. It is also imperative that UVs be able to accurately determine their roll and pitch position. This information is used to maneuver typical UAVs and is used for safety on most UGVs.

Orientation can be sensed by electron sensors or calculated based on passed information. Typically, calculation of orientation is limited to heading. This is usually accomplished by

commanding a known movement, i.e. straight forward, and then using the previous and current position to calculate heading. This type of calculation can be very accurate if position information is very accurate or the calculation is performed over a large movement. Sensed orientation is typically accomplished via magnetometers which provide magnetic force readings on multiple axes. These readings use the magnetic field produced by the earth to determine roll, pitch, and yaw. These readings are heavily influenced by magnetic fields produced by other objects including ferrous metals and electrical current. In dynamic systems these disturbances are typically filtered using gyroscopic readings on parallel axes.

For these reasons it was determined that this processing system be equipped with 3 axis magnetometers and gyroscopes. This would provide adequate orientation information about the state of both UGVs and UAVs.

### 3.1.3 Movement

Movement, although obvious, is crucial to any UV design. To be functional, a UV must have the ability to orient itself or a part of itself. This could be as simple as the movement of a pan/tilt system or as complex as 3D flight from a VTOL vehicle. Although there are extreme differences between the two previous examples they both contain one fundamental similarity: they both control the position of an actuator or multiple actuators.

Examples of actuators include electric motors, thermal bimorphs, hydraulic pistons, relays, piezoelectric actuators, comb drives, and electroactive polymers. All of which transform some type of input signal into motion. In UV designs, this input signal is typically an electrical signal indicating the position and/or speed of the actuator.

This need to precisely control the movement of some aspect of the UV led to the integration of a servo controller into the processing system. The servo controller was chosen based on the fact that most miniature platforms are controlled via small servo motors. In the event that desired actuator is not a servo the PWM signal produced by the servo controller can be converted to supply the correct input syntax.

#### 3.1.4 Process Data

All of the above abilities are fairly useless without some level of data processing. Whether the processing is accomplished at a local ground station or on the UV the data must be processed. This type of processing can be accomplished by small integrated hardware with minimal adaptability to massive multiprocessing machines. Processing systems range greatly in size, power consumption, heat dissipation, computational ability, and peripheral support. Examples of processing boards include Basic stamp, PC-104, Advanced Technology Extended (ATX), ITX, and custom microprocessor designs. These boards allow for a multitude of input and outputs via various ports and support several levels of operating systems and peripheral devices.

When selecting a processing board one must first consider the location at which the processing system will be stored. Processing accomplished at a local ground station has the advantage of almost limitless computational and electrical power. Although this is very inviting the environment in which UVs typically operate (over long distances and typically not line of sight) and the medium by which they transfer data (802.11, serial modem, etc) is severely limiting (discussed in detail in the following section).. For this reason it was decided that the processing board for this adaptable system be located on the UV.

### 3.2 Limitations

When designing an adaptable onboard processing system one must pay a great deal of attention to the limitations of both the platforms on which the system could be used and the environment in which the system could be used. This includes issues related to payload, propulsion, platform limitations, operating environment, and electrical power, all of which will add to the overall complexity of the onboard design.

#### 3.2.1 Payload

Payload limitation is by far the most important limiting factors in miniature UVs. Such limitation requires the sacrifice of larger highly accurate sensors with smaller lighter less accurate sensors. It also limits the use of onboard equipment with high power consumption rates including high power processors, lasers range finders, radars, etc. This is mainly due to the majority of

platforms needing to carry all of the power required to operate the onboard system and platform. This requirement creates an unforeseen payload decrease with every new piece of hardware. The designer is forced consider both the actual weight of any hardware added to the onboard system and the weight of the extra power required to properly operate the hardware.

The limitation imposed on the size and weight of hardware added to any onboard system is always a tradeoff between the hardware's ability and the overall dimensions and weight. A designer must consider that any reduction in the ability of the hardware will most likely have to be overcome through software. The designer should also be aware that extra strain placed on software may cause currently working software and hardware to fail.

Payload is also crucial when focusing on the dynamics and safety of a UV. Even payloads that fall under the maximum abilities of the vehicle may still create unforeseen complications. First, any increase to the total weight of the vehicle will affect the overall dynamics of the vehicle. This alteration could be either positive or negative depending on the hardware and platform. For example, a well placed weight on a UGV platform may lower the center of gravity decreasing the possibility of a roll over or even decrease the overall vibration of the vehicle. It is also possible that this same weight could lower the ground clearance of the vehicle increasing the possibility of the vehicle becoming high centered. Second, incorrectly placed payload can severely alter the vehicle's dynamics and cause serious safety issues. For example, a seemingly small payload placed too far out on a fixed wing aircraft could cause the wing to break under high wind or could cripple the ailerons in a side wind.

### 3.2.2 Propulsion

When designing an onboard system one must consider the limitation imposed by the propulsion of the platforms that will be utilized. In the area of miniature UV platforms the types of propulsion are typically limited to jet, electric, methanol, and gas. Each has its limitations for overall UV performance but the discussion will be limited to the limitations that affect the design of the onboard processing system.

Although electrical, methanol, gas, and jet propulsion systems are very different they will each have some effect on any nearby or direct mounted object. For electrical propulsion this includes large magnetic fields. These are typical in platforms that can use well over 20 amps of current. These spikes can have adverse effects on unshielded wires or any sensors that rely on magnetic fields for accurate measurements (i.e. electronic compasses). Methanol and gas

propulsion systems typically expel a large amount of unburned oil and gas. This can be very hazardous to any electronics that are not environmentally protected. Last, jet propulsion exposes its surroundings to a great deal of heat and noise. This could cause damage to sensitive sensors or hardware placed near the engine.

### 3.2.3 Platforms

All UV platforms have some type of limitation. Limitations may greatly cripple the functionality and safety of the UV if they are not handled with care. Limiting factors in miniature UV's include vibrations, freedom of movement, control difficulties, payload limitations, and safety.

Vibrations are a very serious issue when designing an onboard system. This is mainly due to the sensor noise caused by vibration. Many UV platforms rely on rates and accelerations, provided by gyroscopes and accelerometers, for accurate vehicle functionality. One example of the severity of this noise is visible in Figure 4, where the level of noise from a static object is approximately 0.015 Gs compared to an object hard mounted to an engine in low ideal which is approximately 0.6 Gs. This is 40 times the amount of noise in a static object. The level of severity is highly dependent on the mounting method, platform type, and propulsion type.

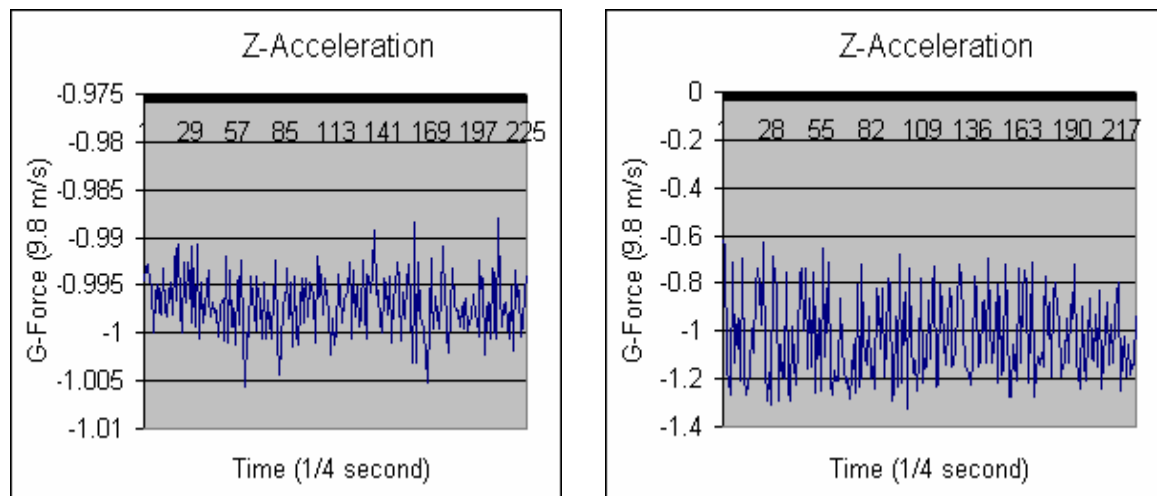


Figure 4: Z Axis Vibration from VTOL, Engine Off (left) and Low Idle (right)

Vibration is also an issue with the physical stability of the onboard system. Many electronic parts are built around the assumption that they will be used in a semi-static environment. When these types of electronics are placed in high vibration and shock



environments their probability of failure increases greatly. Great care must be taken to assure that the capabilities of the hardware are not exceeded. This can be accomplished by using components specifically designed for high vibration environments or by reducing the amount of vibration felt by that component. This can be done using vibration reducing mounts in key areas. Great care must be taken to ensure that vibration reduction material does not cause amplification of vibration due to the frequency of the vibration.

Freedom of movement and control difficulties are also a concern when dealing with UV platforms. This is apparent when one considers the extreme differences in control, even teleoperation, when dealing with 2 axis operating vehicles (UGVs) and 3 axis operating vehicles (UAVs). The main issues being the need to accurately and quickly determine the position, orientation and rates in three dimensions rather than two dimensions. This can have a multitude of effects on the vehicle. For example, consider what must be controlled when moving a UV forward. A UGV with Ackermann steering must assure that its turn angle is zero (steering control) and must have some forward rotation on the tires (acceleration control). A UAV VTOL must assure that the vehicle does not lose altitude (collective control), that its main rotor turns (throttle control), that it does not roll to either side (aileron control), that it does not yaw left or right (heading control), and that it has some forward motion (pitch control).

Safety, although not entirely obvious, should be the most important of all concerns when dealing with any UV. All UV's are dangerous when not given the proper care and attention they demand. Typical UVs, even miniature ones, are large enough to damage property and causes severe injuries. This can be limited to cuts and bruises caused by a run away UGV or the death of a college caused by a VTOL's main blades. One must design onboard processing systems that do not disturb the natural safety precautions on the utilized platform and account for any safety issues that the onboard system may impose on the UV. This could include switches that shut down components in the event of failure, teleoperation takeover, or even redundant components.

#### 3.2.4 Environment

The environment in which a processing system functions has a great effect on the design of any processing system. This effect is typically limited to the type of enclosure in which the onboard system is contained but can also reflect directly on the hardware itself. Specifically, hardware designed for a particular environment can alleviate constraints on the enclosure and

improve overall system's performance. This could include industrial designed hardware which is typically more tolerant of heat variations, moisture, and radiation.

Although some hardware may reduce constraints on the enclosure they are typically expensive and may go far beyond the requirements of the UV's operation. In these instances special attention should be taken to ensure that the enclosure can support all of the required operating environments. This includes environments that are exposed to chemicals, extreme heat and cold, radiation, moisture, pressure, etc. One must also assure that enclosure constraints do not directly conflict with onboard system's functionality. For example, an air tight enclosure will lose the ability to measure barometric pressure which is commonly used to measure altitude. One must even consider the type of material from which the enclosure is made. Materials that do not conduct heat will increase the overall temperature of the enclosed hardware, ferrous metals will have adverse effects on electric compasses, and some materials are too soft or rigid for a particular design.

### 3.2.5 Electrical Power

Power is a very limiting factor in any hardware design but especially limiting in miniature unmanned vehicles where payloads are highly limited. Most UVs require that all electrical power be carried onboard the platform. This requirement puts a great strain on the designer to assure that each piece of hardware is absolutely necessary and power efficient. It also forces the designer to consider power sources that have high power to weight ratios. Examples of such power sources would be lithium batteries (polymer and ion) and onboard generators.

Lithium polymer and ion batteries allow hardware to utilize power that is low in weight, high in power output, and rechargeable. Lithium batteries have a great advantage over Nickel Metal Hydride and Nickel Cadmium batteries due to their three and four times higher power to weight ratio respectively [27]. Although lithium batteries are very appealing to onboard system design, it does come at a price. Lithium batteries have very sensitive discharge and recharge ratios and are very sensitive to shock. Incorrect care for these batteries can easily result in explosions and fire.

It is also appealing to allow a platform to supply its own electrical power via an onboard generator. Although this choice would seem optimal it does require several sacrifices. First, an onboard generator adds weight to the design pulling from an already taxed payload. Second, the

power required to operate the generator is equal to or greater than power output by the generator. For example, a gasoline powered platform will use extra combustion to produce electrical power. This will increase the amount of fuel spent at any given time. Basically, an electrical generator will reduce to overall platform endurance.

## Chapter 4

### Platforms & Hardware

Hardware is the building block of all unmanned vehicles. Decisions made about hardware can significantly decrease or increase the complexity and functionality of an unmanned system. For this reason great effort is taken to effectively describe and justify the chosen hardware.

#### 4.1 Platforms

The utilized UAV platform is a Raptor 90 SE VTOL with the following characteristics:

- Manufacturer: Thunder Tiger
- Rotor Diameter: 710 mm (Symmetrical)
- Dry Weight: 5.8 kg
- Dimensions: 130x27x48cm (w/o Blades)
- Payload Capacity: 4 kg
- Endurance: 18 min
- Battery: 4.8 V (2.6A) NiCad
- Fuel: 30% Nitrous (Methanol)
- Engine: OS 0.91 C-Spec

This platform was chosen due to its high power output and small size. The platform has been shown to have relatively low vibration and an ability to handle wind gust exceeding 15 mph.

The utilized UGV platform is an E-MAXX RC truck with the following characteristics:

- Manufacturer: Traxxas Corporation
- Max Speed: 30 Mph
- Drive system: Shaft-drive 4WD
- Dry Weight: 3.8 kg

- Dimensions: 49x41x27cm
- Endurance: 40 min
- Battery: Dual: 7.2V 8Ah LiPo
- Motor: Dual Titan™ 550
- Speed Controller: EVX FWD/REV electronic

This platform was chosen due to its rugged nature, wide wheel base, adjustable suspensions system, and low center of gravity.

## 4.2 Hardware

The hardware components of the onboard system consist of:

- 1.2 GHz EPIA Processor
- Via Embedded motherboard
- Unibrain Firewire Camera
- Microstrain 3DM-G IMU
- 1 Gig 266 MHz RAM
- 1 Gig Compact Flash
- Compact Flash to IDE adapter
- Motorola M12+ GPS Receiver
- 8 Channel Servo Controller
- 200 W Power Supply
- 11.1 V LiPo Battery
- 802.11B Cardbus

This configuration was chosen because of its high computational capabilities, various Input/Output (I/O) ports, size, low heat emission, and cost. Figure 5 depicts the overall concept for the onboard processing system as well as connection descriptions.

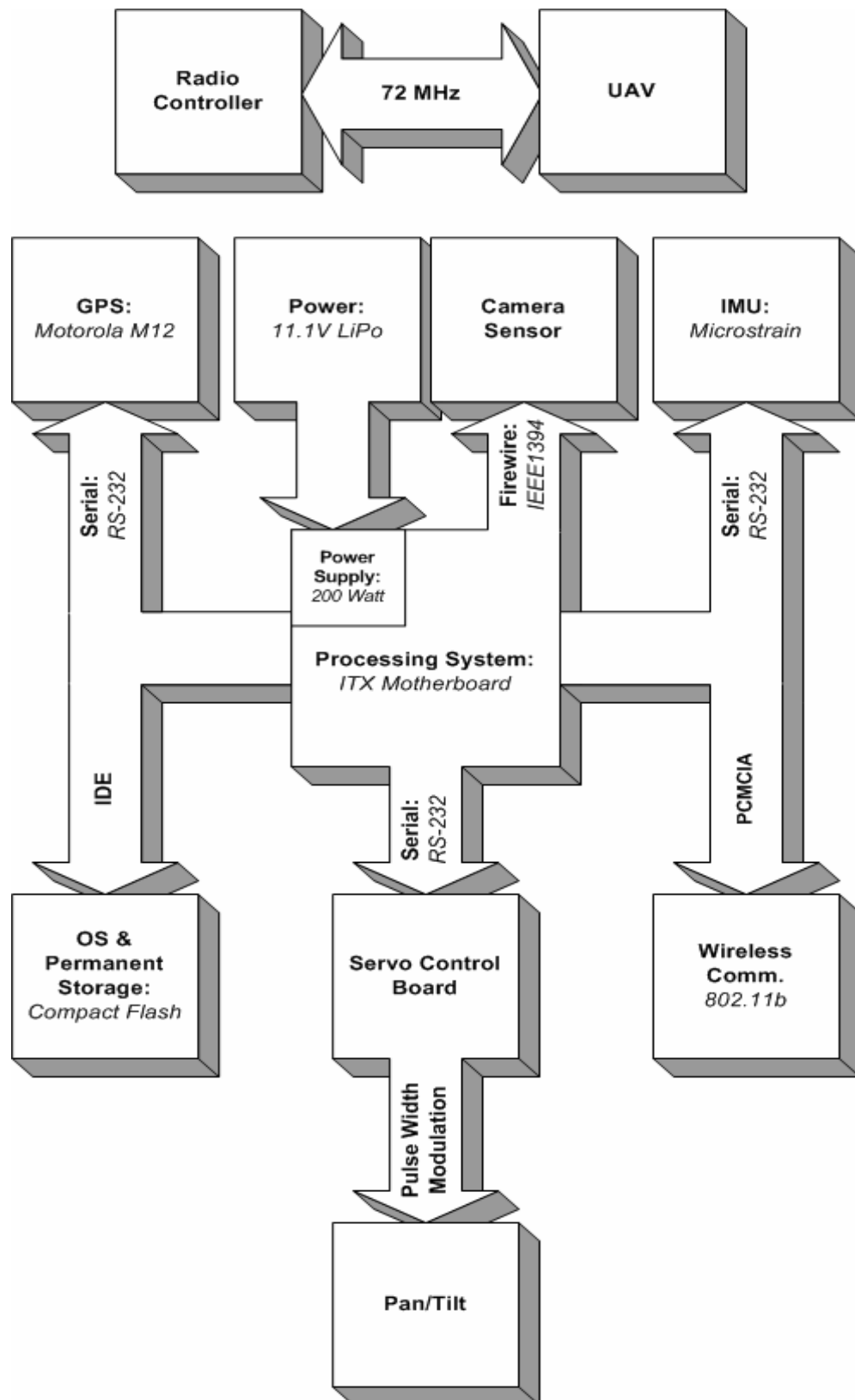


Figure 5: Conceptual System Diagram

#### 4.2.1 Enclosure

The onboard processing system is packaged into a 32x19x5 cm basswood box mounted on a lightweight aluminum sheet, see Figure 6. This sheet is mounted directly to the VTOL's skids via rubber insulated pipe clamps or to the UGV by rubber insulated aluminum sheets. The slim design of the enclosure allows for mounting of the hardware without modification to the standard carbon fiber skids of the VTOL and allows for a lower center of gravity on the UGV. The box is coated with a gas proof heat shrunk plastic typically used to coat model airplanes. Basswood was chosen for the enclosure due to its lightweight nature and its lack of electrical conductance.

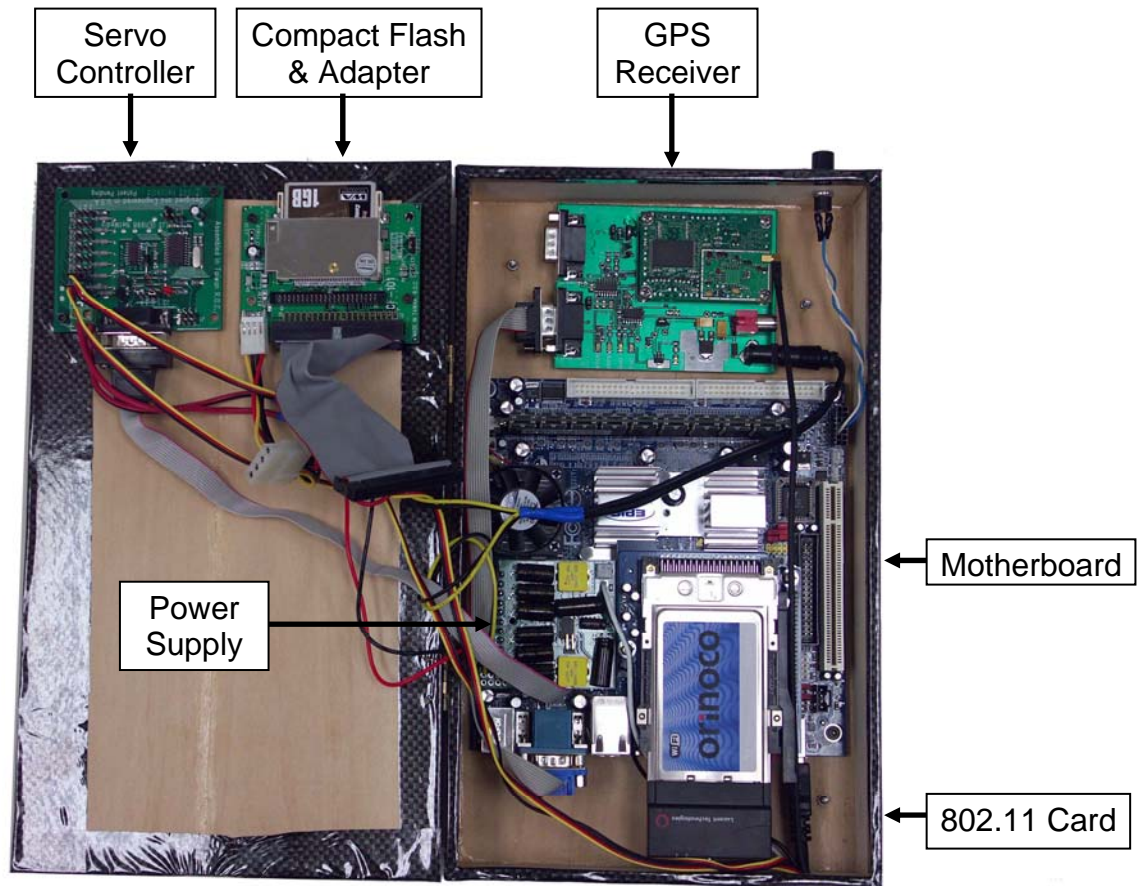


Figure 6: Onboard Processing System in the Enclosure

#### 4.2.2 Camera & Servo Controller

For the VTOL platform, the camera was shock mounted directly to a Lynxmotion pan/tilt unit, Figure 7. This unit was, in turn, hard mounted directly to the underside of the Raptor's servo tray. The pan/tilt system consists of two Futaba S3004 servos that are interconnected by 1/3cm laser cut Lexan. This setup allows the camera to pan and tilt up to 90°. Servo commands are issued by the eight channel servo control board located within the enclosure.

For the UGV platform, the camera was hard mounted to the front bumper of the vehicle and panning motions were assumed to be controlled by the direction of the vehicle.

To fully utilize the potential of the onboard system for the UGV the servo controller was directly connected to the speed controller and steering servo of the vehicle. This modification allows the entire movement of the platform to be controlled via the onboard processing system. Details of this implementation are discussed in chapter Five. This type of implementation was not considered an option on the VTOL platform due to safety concerns associated with the possibility of uncontrolled movements.

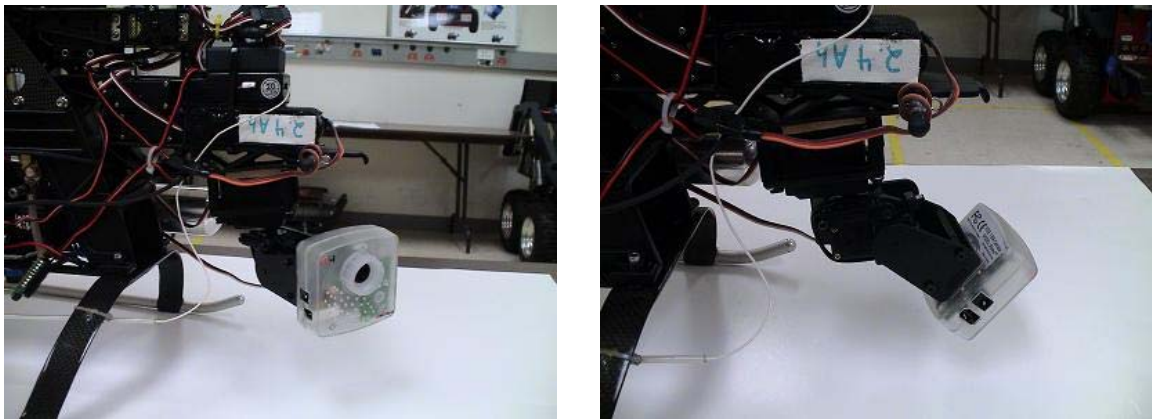


Figure 7: Pan/Tilt and Camera Mounted to the Servo Tray of VTOL

#### 4.2.3 Orientation & Position Sensors

To satisfy the need for orientation data required by many software algorithms [31] a Microstrain 3-DMG was mounted to the UV. This device allows the onboard system access to the current orientation of the platform at up to 100Hz. The sensor is capable of sending both raw and gyro stabilized data and can supply the processing system with Euler angles, Quaternion vectors, roll rates, accelerations, and magnetic direction.



The onboard system is designed to receive GPS coordinates via the Motorola M12+ GPS receiver located within the enclosure and the active antenna mounted to either the horizontal fin of the VTOL or the top of the enclosure for the UGV. The horizontal fin is covered in an aluminum tape to assist in reception.

#### 4.2.4 Electrical Power

Power for the onboard system is supplied via the 11.1V 4Ah Lithium Polymer (LiPo) battery mounted on the lower front section of the boom for the VTOL and the undercarriage of the UGV. LiPo's were selected based on their high amperage, low weight, and small packaging. Power distribution to the hardware components is controlled by the 200 Watt ATX power supply. The power supply plugs directly into the motherboard allowing the unit to add nothing to the physical dimensions of the hardware.

#### 4.2.5 Data Processing Board

The median for all peripherals of the onboard system is an EPIA VIA M2 motherboard. This 1.2GHz ITX motherboard provides multiple I/O interfaces, RAM, and CPU on a single board. The most commonly used I/O interfaces along with the interface type and number available on the board are described in Table 1. The ITX board has distinct advantages over typical PC-104 boards that require separate boards for processor, ram, interfaces, etc. Another drawback to the PC104 form factor is its difficulty in keeping the standard current. The PC104 standard uses a 16 bit ISA bus operating at 33 MHz. This is technologically inferior to the standard PCI and PCI-X system buses with a 32-bit standard operating at 66 and 133 MHz, respectively. The ITX motherboard also allows for a multitude of sensor suites and I/O devices to be added and removed from the onboard system with virtually no modification to the overall design due to low level integration of I/O ports. The ITX form motherboard also allows for an extremely thin designed enclosure where PC-104 boards are typically limited to a stack type configuration.

Table 1: EPIA MII Device Support

Port Type	# Available	Interface Type
IEEE1394	1	6 Pin Standard
USB	4	2x 5 Pin Standard, 2x Board Pinout
Serial	2	1x RS232, 1x Board Pinout
Cardbus	1	Type I/II
Compact Flash	1	CF Slot
Ethernet	1	RJ45
S-Video Out	1	Standard 5 pin
Composite Video	1	RCA
LPT	1	Board Pinout
VGA	1	VGA
PS2	2	1x Keyboard, 1x Mouse
PCI	1	PCI Slot
IDE	2	40 Pin IDE
RAM	1	PC 233

#### 4.2.6 Communication & Data Storage

All communication with the onboard processing system is handled via 802.11 B. This is supported by an Orinoco Peripheral Component Microchannel Interconnect Architecture (PCMCIA) card. This card interfaces directly with the motherboard via the supported PCMCIA slot. To support extended range this particular card is equipped with an external whip antenna. This antenna is mounted horizontally directly behind the enclosure for the VTOL and vertically at the front of the vehicle for the UGV.

The remaining hardware consists of a 1 Gig compact flash and IDE to Compact Flash (CF) adapter. The compact flash drive is responsible for the storage the operating system and hardware drivers. The CF adapter allows for a seamless interface between the software and the motherboard.

### 4.3 Assembly

Due to the sensitive dynamics of VTOL aircraft, special attention was taken to select and assemble all hardware. VTOL roll and pitch movement is typically directed around the Center of Gravity (CG) [8]. This center of gravity is typically designed to reside on the main shaft of the platform approximately half way down the frame. This centrally located CG allows the helicopter to perform highly aggressive maneuvers in very confined areas.

To avoid obstruction of the VTOL's naturally aggressive abilities extreme care was taken to select hardware that could be assembled and mounted in a way that would minimally alter the CG. This involved a complete design that would weigh significantly less than the maximum payload of the platform, in this case a weight of approximately 2.0 kg (almost half the maximum payload). Minimal obstruction also included mounting the onboard system in a manner that would keep the CG centrally located, see Figure 8.

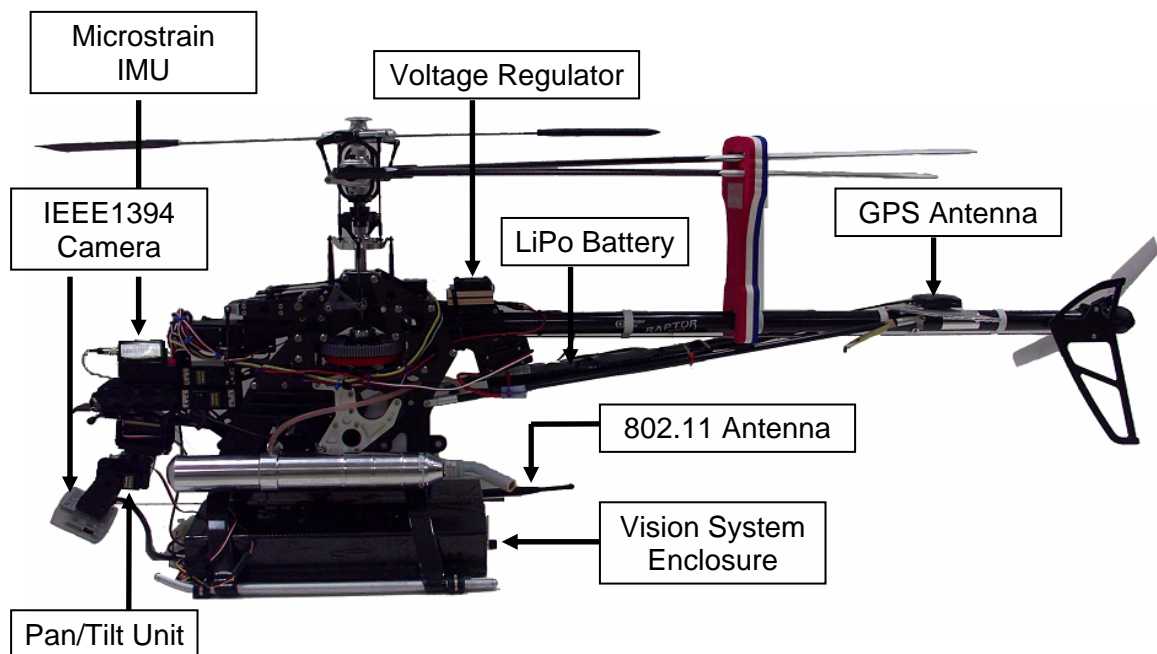


Figure 8: Raptor 90 Equipped With Onboard Processing System

Although the dynamics of the UGV are not as sensitive as the VTOL's, special attention must be taken to assure that platform is resilient to rollovers, high centering, and ground strikes, see Figure 9. To prevent rollovers the onboard system is mounted as close to the platforms natural CG as physically possible and the stock shock mounts are moved away from the CG to increase the wheel base of the platform. To prevent high centering and ground strikes heavy duty springs

were added to the suspension system. This forces the shocks to become stiff causing the suspension system to react more aggressively to vertical forces.



Figure 9: E-MAXX Equipped With Onboard Processing System

#### 4.4 Discussion

It is noteworthy to mention that the abilities of this processing system are highly unutilized. The capabilities of the processing system can extend to fully autonomous control of a multitude of UV platforms. The hardware for this processing system is also highly reconfigurable due to the large number of varying I/O ports and high processing capabilities. This processing system could be easily configured for obstacle avoidance, infrared sensing, and a multitude of other tasks.

## Chapter 5

### Software

#### 5.1 Operating System

To select the operating system for the onboard system, several key requirements were identified like the IEEE 1394 and PCMCIA device support as well as installations that require less than 500 megabytes. These requirements were based on the need to support the Unibrain Firewire camera, Orinoco PCMCIA card, and the desire to have an installation that was less than half the size of the available RAM. Although the first two requirements are straight forward the third one does require further explanation.

Compact Flash cards are solid state storage that deteriorates with every write to the device. This becomes a considerable issue when one considers the number of writes made to permanent storage by the operating system. For this reason it was decided that the compact flash drive would only be used to load the operating system into memory. From that point all operations of the operating system would be performed in RAM. To allow the operating system to have a sufficient work area after being loaded into RAM the operating system had to be sufficiently smaller than the available RAM (1 Gig).

For the above reasons the Slackware 10.0 installation of Linux was chosen. This installation provides support for both PCMCIA and IEEE 1394 devices via its 2.4.26 kernel. The Slackware installation also provides support for low level customization during installation. Specifically, it provided the ability to remove all graphical content from the operating system allowing for a very small installation, less than 150 Megabytes compressed. Printer and sound drivers were also removed to bring the complete installation to approximately 92 Megabytes compressed.

#### 5.2 GPS & Servo Control

Software for the onboard system's GPS receiver included a single serial communication program with the ability to efficiently parse the serial messages. This was accomplished using

the National Marine Electronics Association (NMEA) protocol adopted by all current GPS receivers. This allows the onboard system to remain robust for future hardware updates. The receiver also supports a faster Motorola specific protocol that was deemed unnecessary for our requirements.

Servo control software was written to allow both camera movement via the pan/tilt mounted to the VTOL and autonomous control of the UGV. This is accomplished by passing a character string, via serial communication, to the servo control board. The character string corresponded to one of 255 possible positions for each servo connected to the servo controller. This allows the VTOL's pan/tilt to take one of 65025 positions and allows for fairly high control of the UGV.

### 5.3 Communication

A client/server program was written to handle all status communication between the onboard system and all other off-board devices. The software was designed to dedicate a single port to all system status messages. This software would activate on boot and would only communicate status data upon a successful socket connection and status request from another device. The UV was chosen to act as the server machine to decrease bandwidth usage and to allow the onboard system to function regardless of network connection. Status data included current images from the onboard camera and GPS coordinates.

### 5.4 Object Tracking

The onboard system was also programmed to track objects utilizing the VTOL's pan/tilt system, see Figure 10. Specifically, software was written to identify objects within some threshold of a predetermined color and size [18]. Once an object was identified the center pixel of the object was approximated. Once the pixel was identified the code determined if the pixel was located within the center threshold of the image. The center threshold was determined to be  $\pm 10$  pixels. If the pixel was located within the center threshold both pan and tilt were held in place. If the pixel was not found to be within the center threshold it was determined if the pan, tilt, or both thresholds were broken and in which direction they were broken. This code was combined with servo controller code and used to move the pan/tilt one servo position per threshold violation.

Once the tracking process is initiated it continues until the object no longer appears in frame or the hard limits of the pan/tilt are reached. If the object disappears from frame, as determined by the object recognition software, the pan/tilt holds position for up to 30 frames before returning to a neutral position. If the object reappears the tracking process continues. If the hard limits of the pan/tilt are reached the position is held until it disappears from frame or moves in a direction that does not violate the hard limits of the pan/tilt.

Details involving the validation of software, including GPS & tracking, are discussed in detail in chapter Six.

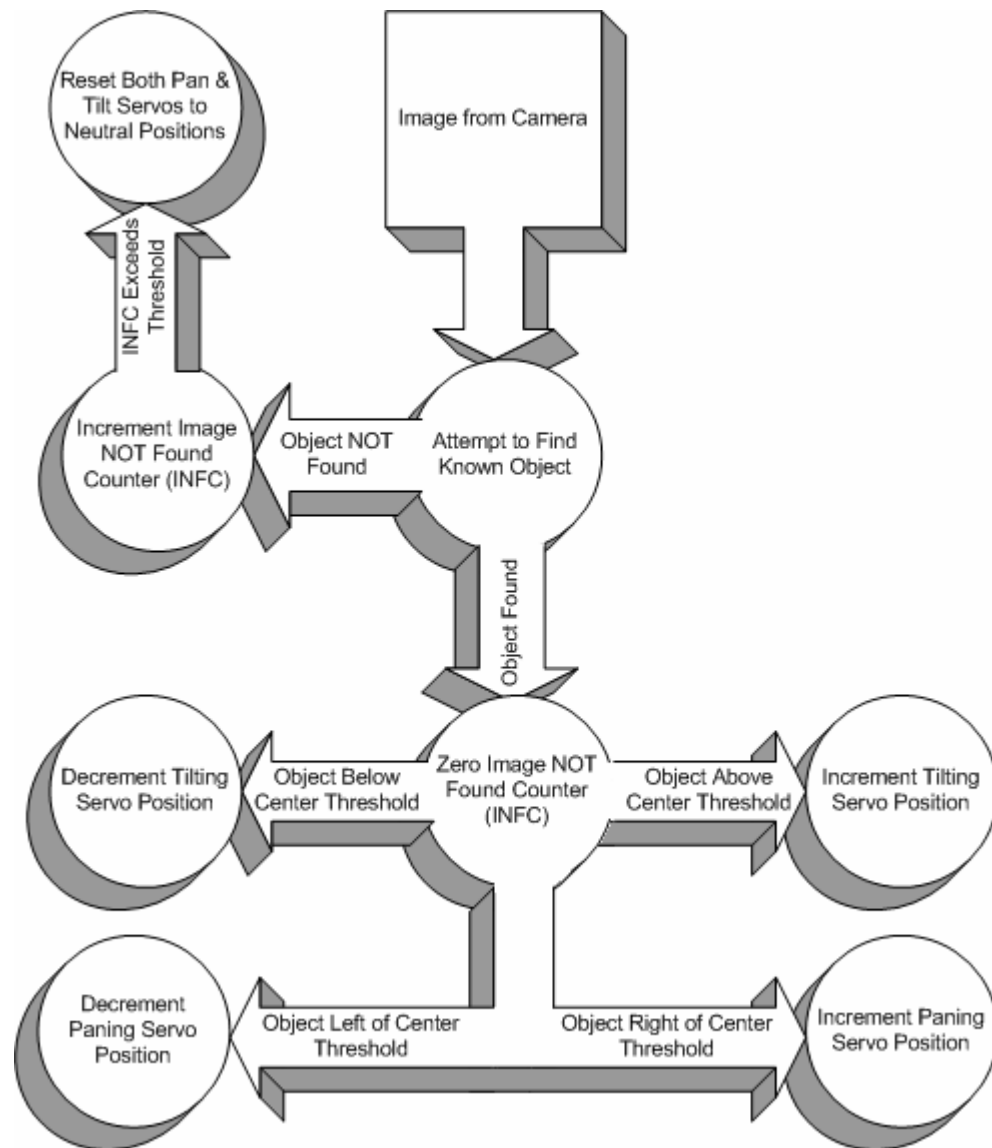


Figure 10: Diagram of Tracking Software

## Chapter 6

### Experiments

In order to validate the onboard processing system and quantify results several experiments were performed. These included experiments for onboard system power consumption, ground versus onboard processing, vision tracking, platform payload limitations, overall system performance, teleoperation, and waypoint navigation.

#### 6.1 Onboard Processing Experiments

##### 6.1.1 Electrical Power Testing

The first experiment performed was to verify that the onboard system could sustain, via the onboard LiPo batteries, as long as the maximum endurance of the utilized UAVs. Due to the nature of LiPo cells an 11.1V battery is considered completely spent when it reaches a voltage of 9 V (this is 3V per LiPo cell). Lowering the voltage below 3V per cell will destroy the battery [14].

To verify the run time of the onboard system it was assembled in full and attached to a fully charged battery. The entire onboard system was then powered and allowed to run in an idle state. Idle in this situation refers to the operation of system level processes only. This resulted in Central Processing Unit (CPU) utilization between 0 and 5 percent. During the experiment GPS coordinates were transmitted by the receiver but ignored and the servos were command to a neutral state and held in position. The onboard system operated for approximately 2.0 hours before the battery voltage reached 9V.

Second, the onboard system was again attached to a fully charged battery and booted. The operating system immediately ran a user level process that grabbed and filtered images from the onboard camera. This process kept CPU utilization between 98 and 100 percent. The onboard system also served a wireless connection providing GPS coordinates to an external



device. The onboard system was operated continuously for 40 minutes before battery voltage was measured to be 9V.

### 6.1.2 Ground Versus Onboard Processing

The second experiment performed was to quantify the processed frame rate that could be achieved and to compare this result to a previous experiments using off-board processing [18]. The software utilized for processing the frames was tasked with identifying a simulated mine, black orb, in varying lighting and background. This was an exact copy of the software utilized in an off-board processing experiment.

Experiments showed frame rate acquisition and processing at a rate of 80 to 120 frames per second (fps) using image resolutions of  $160 \times 120$  pixels. This exceeded camera limitations which could only grab frames at a rate of 30 fps. Experiments with an off-board processing system, utilizing a 900MHz video transmitter, showed a maximum realized frame rate of 15 fps using image resolutions of  $320 \times 240$  pixels. This limitation was mainly due to the Firewire driver for the video capture device which utilized DV format image,  $720 \times 480$  pixels and color depth of 24 bit, at 30 fps which was downsampled to a usable lower resolution image [18]. It is also noteworthy to mention that ground processing resulted in a high number of false positive identifications caused by transmission noise and data loss. This type of false positive identification was removed with the use of the on-board system.

### 6.1.3 Vision Experiments

Pan/Tilt tracking was also tested to validate functionality. First, experiments were performed to determine the resolution of the servo control. This was accomplished by mounting a protractor to the servo and measuring commanded movements. Experiments throughout the entire range of movement showed a resolution of approximately  $0.765^\circ$ . Next, lab experiments were performed to validate correct motion. This was performed by initializing the object recognition software, mentioned in the previous experiment, to identify black objects. A student with one black shoe then proceeded to walk around the room at a normal pace while the onboard system tracked the shoe. Last, the onboard system was taken outside and hovered at approximately 80 feet above the ground and 125 feet from a heavily trafficked road. The onboard system successfully identified and tracked black vehicles as they passed at approximately 50

mph. Note that the software was coded to ignore multiple objects for this experiment and only identified and tracked single objects within the frame.

## 6.2 VTOL Experiments

### 6.2.1 VTOL Payload Limitations

The next experiment performed was to gain insight into the realistic payload capabilities of the VTOL platform. First, the VTOL was fitted with a small aluminum plate across the skids to which blocks of weighted aluminum would be added. The platform was then powered and flown at a starting payload of 2.5 lbs. Every consecutive flight increased the payload to the platform by 8 ounces. This continued until either the pilot deemed the vehicle unsafe to fly or the vehicle simply failed to lift the weight. At a payload of 10.5 lbs the VTOL was taken to a hover at approximately 10 ft where the vehicle was unable to sustain altitude for longer than 2 min. To ensure personal safety and longevity of the equipment the maximum payload set for this vehicle was set at 8.5 lbs. This was deemed the optimal payload by the pilot based on vehicle responsiveness.

### 6.2.2 Naval Surface Warfare Demonstration

Next, experiments were performed at the Naval Surface Warfare Center in Panama City. The VTOL UAV was tasked with identifying a target object (black orb) and presenting an estimated GPS coordinate for that object to an unmanned ground vehicles (UGV) in the area, Figure 11.

The helicopter was first teleoperated through a series of six GPS coordinates at an altitude of approximately five meters. This altitude was chosen based on the field of view of the camera and to prevent false positive identifications experienced at lower altitudes from grass color and shadows. Each GPS coordinate was approximately fifteen meters from the previous GPS coordinate and arranged in a raster scan configuration. This resulted in a search area of approximately 450 square meters. The desired object was then randomly placed within the search area. Upon visual detection of the designated object the VTOL was teleoperated to a hover and remained in position until a ground robot arrived. The hovering position of the VTOL was

utilized as the GPS estimation of the object. This was deemed a valid estimation due to the almost vertical positioning of the onboard camera.



Figure 11: VTOL and UGVs Searching for a Simulated Mine (Black Orb)

Identification of the object was handled by onboard vision algorithms utilizing the color and size of the object [18]. Upon identification of the object an internal flag was set. This flag was passed to the ground station upon status request, typically once per second. After receipt of the flag the ground station tasked a local ground robot to the estimated position. Figure 12 shows a screenshot of the VTOL requesting help from a UGV after visual detection of a possible “mine”. Upon arrival at the estimated GPS coordinate, the ground robot began a spiral search for the desired object and the VTOL was released for further searching.

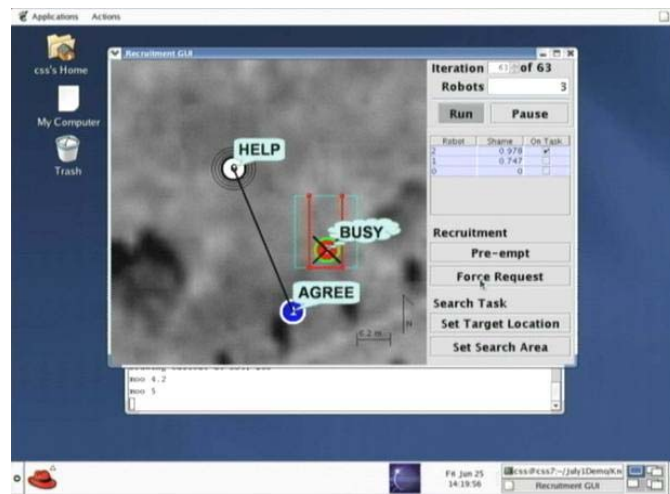


Figure 12: Ground Station GUI Visualizing the VTOL’s Request for a UGV

### 6.2.3 Traffic Surveillance

The last UAV specific experiment performed was to achieve an initial understanding into the potential and problems with VTOL based traffic surveillance. This was accomplished by utilizing the onboard processing system and the VTOL UAV, radio controlled, to retrieve aerial video of traffic.

Video produced by the processing system showed several issues. First, distortion in the lens created a “rounded” effect on the images, see Figure 13. Roadway that was undoubtedly flat appeared curved in the image. This also caused distortion to the vehicles traveling on the roadway and made automated vehicle identification somewhat difficult.

Second, the video was very out of focus. Although it seems that a minor adjustment would fix the issue it is almost impossible to know the altitude and angle at which the VTOL will reside while monitoring the traffic. Hence, it is very difficult to focus the lens before flight suggesting that an auto focus lens or onboard controlled focus would prove useful.

Last, the captured images revealed issues based around iris control. The Fire-I camera attempts to simulate iris control through software but only bases this control on initial measurements or when light entry exceeds some large threshold. Since the camera is typically only inches from the ground when powered on it is heavily shadowed by itself and the VTOL. As the VTOL gains altitude more light enters into the iris but typically does not exceed the preset threshold. This results in images that lose distinction in both color and clarity, see Figure 13.



Figure 13: VTOL Images Showing Camera Distortion & Poor Iris Control (left) and Poor Focus (right)

Other issues noted during these experiments were the amount of aerial obstacles present around roadways, including power lines, tree lines, light post and signs along with the difficulty involved in finding emergency landings in areas.

### 6.3 UGV Experiments

#### 6.3.1 Teleoperation

The first experiment performed on the UGV platform was teleoperated control. This was done to validate the claim that the onboard system was both generic and highly adaptable.

The onboard system was first mounted to the UGV with one minor modification: all platform servos (speed, gear selection, and steering) were connected directly to the servo controller. This removed the control from the standard radio controller and gave it to the onboard processing system. Code was then implemented that gave command of the vehicle to any machine with login permissions. The user was then able to drive the vehicle, via the keypad, using a remote machine. The user was also able to utilize the same software that was tested and implemented for the VTOL including video and status passing as well as GPS and IMU data.

It is noteworthy to mention that time required to pull the onboard system from the VTOL, mount it to the UGV, and have the onboard system physically fully operational is about 15 minutes.

#### 6.3.2 Autonomous Navigation

The last experiment performed was waypoint navigation of the UGV. This accomplished to validate the claim that the onboard system possesses the ability to effectively control a miniature vehicle.

The onboard system was first given a list of desired GPS waypoints. The onboard system was then command to move the platform to these waypoints stopping at the last one. This was accomplished by comparing the current GPS coordinate of the UV to the next waypoint. These two positions were then used to calculate the easterly and northerly error. These two errors were used to calculate the angle from north from the UV to the waypoint. The heading of the UV was

then requested from the IMU and subtracted from the error angle. This angle was used as the steering angle of the UV's front wheels.

Make note that due to the limitations of Ackermann steering and the design of the E-MAXX the vehicles turning angle was limited to  $45^\circ$ . Any calculated angle above  $45^\circ$  or below  $-45^\circ$  was adjusted to this maximum in that direction.

The speed of the UV was controlled by both the distance from the waypoint and the turning angle of the vehicle. The larger the distance of the UGV from the waypoint the faster the UGV was command to go. This was limited by a maximum speed of approximately 10 Mph. This speed was further reduced based on the turning angle of the front tires. This was to avoid roll over of the vehicle caused by high speed turns. The UGV was also lower limited in speed to assure that the vehicle did not stop in the event that uneven terrain was reached.

The UGV successfully navigated several patterns of waypoints on uneven terrain through heavy grass, see Figure 14. Videos of both indoor and outdoor autonomous navigation can be viewed at [www.csee.usf.edu/~rdgarcia/Videos/EMAXX/](http://www.csee.usf.edu/~rdgarcia/Videos/EMAXX/).



Figure 14: E-MAXX Autonomously Navigating Waypoints

## Chapter 7

### Summary & Future Work

This chapter summarizes the work related to this thesis along with a possible future related research. Two primary contributions were described by this work. First, the identification of key characteristics of an onboard system for UVs is identified. This allows for a high level validation of both hardware and software for typical UV processing systems. It also provides a design template for a reconfigurable, platform independent, processing system for UVs.

Second, this thesis provides a detailed design of an adaptable onboard processing system that is both computationally powerful and easily adapted along with its implementation. This is validated through both lab (indoor) and field (outdoor) experiments. This implantation also assists in the validation of key characteristics of a UV onboard system.

#### 7.1 Future Work

One drawback to the onboard system described above is the lack of a manual takeover switch. This limits the safe testing and operation of any autonomous control. Although this is typically not an issue with UGVs it is a must for all UAVs especially when in the testing phase of any research. Integration of a safety switch would also help to prevent both injuries and equipment damage.

Although this thesis's implemented onboard system follows the constraints described in chapter 3, there are many possible variations. These can include onboard systems designed around a very high budget that can utilize custom designed hardware and state of the art technology. Examples would be 25Hz differential GPS, satellite data transfer, high rate accelerometers and gyroscopes, and custom platforms. This could also include onboard systems designed completely around Commercial Off the Shelf (COTS) products.

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## Appendices

## Appendix 1: Vision System Tables

Table 2: Existing Vision Systems for VTOL Platforms

Institution	Machine Vision Techniques Utilized	Processing Type	Vehicle (Platform)
Berkeley University [32]	No details provided	No details provided	BEAR
Georgia Tech [26] [15]	Edge detectors, morphing, Statistical pattern matching	On- board	Rmax by Yamaha
Standford University [39] [40]	YUV color segmentation, signum of Laplacian of Gaussian (sLoG)	On-the-ground	Hummingbird Aerospace Robotic Laboratory at Standford
MIT [4]	Template matching	On-the-ground	Black Star by TSK
Rose Hulman IT (RHIT) [9]	Template comparison	On-board	Bergen Twin
IT Berlin [22]	No details provided	On-the-ground	MARVIN by SSM Technik
University of Texas [12]	Edge linking matching	On-the-ground	XCell .60
Swiss Federal Institute of Technology (ETH) [4]	No details provided	On-board integrated in camera	Huner Technik
Carnegie Mellon University [2]	Template matching and RGB color	On-the-ground	Rmax by Yamaha
USC [32] [39]	Omnidirectional, optic flow	On-board	Bergen Twin
Southern Polytechnic State Univesity [3]	Stereo vision, Sobel egde detector	On-the-ground	Vario Robinson R22
Linkoping University, Sweden (WITAS) [24]	No details provided	On-board	Rmax by Yamaha

Appendix 1: (Continued)

Table 3: Summary of System Characteristics and Functionality

Institution →		Berkeley	Georgia Tech	Univ. of South California	COMETS* [25]	WITAS+ [24]	CNRS~ [31]
Exprimental setup	Dynamic observer	X	X	X	X	X	X
	Dynamic environment				X	X	
	Static/man-made enviornment	X		X			X
	Known landmarks	X	X	X			
	Natural landmarks				X		
	Calibrated cameras				X		
Capabilities	3D reconstruction /depth mapping		X	X			
	Object identification	X	X	X	X		
	Object tracking		X	X	X		
Methods used	Optic flow			X		X	X
	Motion estimation	X			X	X	X
	IMU data						X
	Template matching	X		X	X	X	

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+ Wallenberg laboratory for research on Information Tech. and Autonomous Systems (WITAS)

~ Centre National de la Recherché Scientifique (CNRS) in France