This report describes the results of an investigation into some of the technical and operational issues associated with using Unmanned Aerial Systems (UAS) for the application of surveillance in support of transportation infrastructure management and security. As part of this investigation a low-cost, miniature, hand-launched aerial vehicle and supporting ground systems suitable for surveillance of highways and traffic infrastructure were developed. Except for the ground station software, this system was built from off-the-shelf components. The ground station software developed was used to enhance ground station operators' situational awareness and simultaneously allow analysis of the data transmitted from the aerial vehicle. In addition, a key system that was developed was an open-source Guidance, Navigation and Control (GNC) software suite for autonomous operation of small aerial vehicles. The culmination of this work was a series flight tests where the UAS developed was used as a tool to enhance situational awareness over a simulated traffic incident or emergency situation. The test consisted of defining a series of waypoints around the area of the simulated incident and launching the miniature aerial vehicle to autonomously fly from waypoint to waypoint.
Acknowledgement

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Executive Summary

This report describes the work done at the University of Minnesota to investigate the technical and operational issues associated with using Unmanned Aerial Systems (UAS) for the application of surveillance in support of transportation infrastructure management and security. The outcomes of this work are:

1. Development of a low-cost, miniature, hand-launched aerial vehicle and supporting ground systems suitable for surveillance of highways and traffic infrastructure. Except for the ground station software, this system was built from off-the-shelf components.

2. Development of software that enhances ground station operators’ situational awareness and allows simultaneous analysis of the data transmitted from the aerial vehicle.


The third outcome was the result of a study to identify the regulatory and technical issues that must be solved before UAS can be routinely used for surveillance in support of transportation infrastructure management and security. One of the conclusions of this effort was that certifying UASs will be easier if certifying agencies have influence over the design of GNC algorithms especially features having to do with fault detection and isolation. An open-source GNC software suite can facilitate building regulatory requirements for GNC systems. The culmination of this work was a series flight tests where the UAS developed was used as a tool to enhance situational awareness over a simulated traffic incident or emergency situation. The test consisted of defining a series of waypoint around the area of the simulated incident and launching the miniature aerial vehicle to autonomously fly from waypoint to waypoint.
Chapter 1

Introduction

This report describes the work done at the University of Minnesota to investigate the technical and operational issues associated with using Unmanned Aerial Systems (UAS) for surveillance in support of transportation infrastructure management and security. The work was accomplished under a research grant from the ITS Institute at the University of Minnesota and a research contract from the Minnesota Department of Transportation (via a subcontract from SRF Consulting Inc.). The objectives of this work were twofold. First, it was to develop an UAS from off-the-shelf components (i.e., develop a "turn key solution"). The second objective was to identify technical and regulatory issue that need to be addressed before UAS can be routinely and effectively used in Intelligent Transportation System (ITS) applications.

The work associate with the first objective resulted in the following outcomes:

- Development of a low-cost, miniature, hand-launched aerial vehicle and supporting ground systems. Except for the ground station software, this system was built from off-the-shelf components.
- Development of software which enhances ground station operators’ situational awareness and allows simultaneous analysis of the data transmitted from the aerial vehicle.

The work associated with the second objective resulted in the following outcomes:


1.1 Report Organization

In what follows the outcomes and the findings of this research project are discussed in detail. To that end, the remainder of this report is organized as follows: First, a detailed discussion of the motivation for using UAS in these applications is presented. The technical and regulatory challenges associated with this application are discussed. Then each project task and its outcome is discussed separately. Concluding remarks and suggestions for future work close the report.
Chapter 2

UAS in ITS Applications

Uninhabited Aerial Vehicles (UAVs) are defined as aircraft which fly without a human operator onboard. They can be flown autonomously or piloted remotely. If they are piloted remotely, they are sometimes referred to as Remotely Piloted Vehicles or RPV. They are designed as either expendable or recoverable platforms [1]. They are well-suited for use as sensor payload platforms to gather remotely sensed data. They span a wide range in size and complexity with some of the largest UAVs being several thousand pounds in weight and have wing spans on the order of 100 feet [2, 3]. At the other end of the size spectrum are the Micro Aerial Vehicles (MAVs) which have a maximum dimension and weight on the order of 15 cm and 150 grams, respectively [2, 3]. A UAV (or MAV) together with the systems on the ground used to interact with it are normally referred to as an Uninhabited Aerial Systems (UAS).

While it is not difficult to imagine military missions for UAS, there are equally many potential civilian and scientific applications [4, 5]. Envisioned civilian applications include forestry surveys, environmental monitoring and power-line inspections. These envisioned applications can be divided into the two broad categories that we in this report call strategic and tactical operations. In simple terms, we define strategic operations to be operations where the aerial vehicle is expected to traverse or cover a large geographical area. These operations are mostly pre-planned and the separation distance between the aerial vehicles and the operators can be very large. This implies that the round-trip travel time for signals between the ground station and the aerial vehicle can range from several milliseconds to a few seconds. Since delays of this magnitude can be dangerous or destabilizing when it comes to control of aerial vehicles, UAVs slated for strategic operations must be capable of a high level of autonomy. On the other hand, we define tactical operations are defined to be operations in and around a small geographical area. Operation can be in response to planned or unplanned events. Because of the proximity of the aerial vehicle to the ground operators, it is possible for that tactical operations to entirely conducted by teleoperation (i.e. non-autonomous). In the case of Intelligent Transportation System (ITS) application, the following two applications demonstrate the difference between what we call strategic and tactical operations:

2.1 Examples of Strategic Applications

A strategic ITS application for which the use of UAS is envisioned is that of mobile sensor networks. The mobile networks will augment installed or stationary sensor networks in gathering data about highway infrastructure [6, 7, 8]. The economic and social motivation for using UAVs in this
application is very compelling. For example, if we consider the state of Minnesota as a typical example, almost 50% of the traffic (measured in miles traveled) is on rural roads (currently 230 thousand rural lane miles), and is increasing at an annual rate of 6% a year. In addition, approximately 70% of all fatalities occur on rural roads (the number of crash related fatalities and rural percentages have remained approximately flat over the last five years) [9, 10]. Rural Minnesota winter weather can present especially hazardous driving conditions—leaving motorists stranded for extended periods. In order to ensure driver safety and rapid incident response, considerable efforts have been made to place ITS traffic sensing and surveillance technologies on specific corridors of Minnesota’s rural roadways. Whether they are permanent installations or placed on movable trailers, they have become an integral part of managing traffic during special events, road construction and work zones, etc.

However, these systems, while still necessary, cannot by on their own provide wide area coverage in a cost-effective manner. The power or other communications infrastructure may not be available. It is simply not practical to manage and build that much infrastructure. Remotely sensed data gathered from moving platforms such as UAS can address the shortcoming encountered with the traditional method of data collection. UAS used in this manner are a complimentary technology to ground based cameras and other ITS technologies. They can be flown over land and traffic directly to problem areas. In doing so, they fill large ‘coverage holes’, providing a ‘big picture’ of traffic flow over large portions of the road network. While manned aircraft can be used in lieu of UASs for this application, there are economic and operational advantages which make the latter a more attractive option. For example, the use of UASs obviates the need for regional airport to house and provide the landing-takeoff-fueling cycles required by manned assets. With adequate 3D feature and terrain knowledge, they may be safely flown at much lower altitudes than manned aircraft (such is the case during low cloud ceilings, etc). This operation is considered strategic because the “coverage holes” of interest may be far away from the site where the UAS is launched or where the remote operators of the system are located.

2.2 Example of Tactical Applications

An example of a tactical ITS application for UASs is that of on-scene traffic, incident or emergency management. In the event of a traffic incident or general emergency, UASs can be used as “force multipliers” for law enforcement and emergency response personnel. In these instances the aerial vehicles can provide services such as mobile-local communication nodes or simply be platforms for Electro-Optical (EO) or Infrared (IR) camera. The recent collapse of the I-35 Bridge in Minneapolis, MN provides an example where the use of UASs would serve as a “force multiplier” for law enforcement and emergency personnel. In this case the UAS could have been used to provide platform for continuous video coverage. This coverage could be used to optimize and organize the rescue and recovery efforts; provide continuous communications between on-site personal and those far away; and finally as camera platforms for photogrammetry reconstruction of the incident. In the case of terrorist attacks that involve, for example, toxic materials appropriately instrumented UAS can be used to map out the boundary of the toxic materials and monitor their spread. Thus, they will prevent the risking the lives of highly skilled personnel that would otherwise have to fly aircraft especially under hostile or toxic conditions.

It should be noted that UAS in this instance fit within the recent framework that addresses transportation security and anti-terrorism measures. This framework, published by the Transportation Security Agency (TSA), emphasizes harnessing ‘dual-use’ technologies that meet the needs of our trans-
portation systems as well as for homeland security roles and law enforcement [11, 12].

The use of UAVs in the above described manner assumes that UAVs can be safely and legally op-
erated in and around populated areas as well as potentially alongside other passenger carrying aircraft
in the National Airspace System (NAS). This, of course, is not the case. It is not clear that UAS op-
erations do not pose an unacceptable level of risk to manned aircraft in the NAS or the population on
the ground.
Chapter 3

Technical and Operational Challenges

Currently, there is no clear and systematic legal or regulatory framework which will allow operation of UAS in the manner described above. That is, while there has been a considerable effort focused on identifying operational concepts which use UASs for traffic management and infrastructure security[6, 7, 8]. As such, there is a considerable amount of research currently underway to develop of operational procedures which ensure safe operation of these vehicles in and around populated areas or the NAS [19].

An important subset of the above mentioned work has focused on developing systematic methods for quantifying risks or dealing with certification issues. Up to this point the analysis of risk associated with these operations has been limited to developing and evaluating methods for preventing collisions between UAVs and other manned aircraft [13]. Recently, researchers at the MIT International Center for Air Transportation have proposed a very promising approach for evaluating safety and risk mitigation measures associated with operation of UAVs [14, 15]. The work in [14] and [15] provides a systematic method for analyzing a given UAVs concept of operation to determine if it meets levels of safety established by regulation. However, while the work in [14] and [15] provides general guidelines on how to perform such evaluations, it does not provide an evaluation of any particular concept of operation.

Related to the challenge of developing operational procedures is a technical challenge of proving that the risk posed by these operations is acceptably small. For aviation operations the regulatory safety requirements are established by the Federal Aviation Administration (FAA) and are normally given as statistical performance metrics. In this context, risk is measured, in part, by the metric known as integrity. Systems are deemed to have an acceptable level of integrity if the risk of hazard to humans when using them is less than some prescribed threshold (for example, one-in-ten-million for certain landing systems [16]).

The difficulty of the integrity problem can be understood by noting the following: The smaller (size and weight) aerial vehicles are, the risk associated with their operation is less. Thus, small, hand-launched aerial vehicles represent an attractive solution. This in turn, presents a unique challenge which is not encountered with other UAVs. With regard to navigation, guidance and control of these vehicles, there are two major challenges. First, while it is possible to adapt and use avionics developed for piloted aircraft in the larger UAVs, new and miniaturized systems have to be developed for smaller UAVs and especially MAVs. There are currently very few off-the-shelf solutions for navigation, guidance and control of small UAVs that are certified to the exacting FAA integrity standards. Second, because of the size and weight constraints, the physical integration of miniature systems and sensors
represents a significant challenge. At these scales the sensors and mission payloads have dimensions and weight is a significant fraction of the overall vehicle dimension and weight, respectively.

The objective of the work described in this report was, in part, to determine whether any meaningful statements about integrity can be made for off the shelf avionics for small UAVs without extensive analysis.
Chapter 4

Project Objectives And Scope

As noted earlier, the work described in the report investigated aspects of both the operational and technical challenges with UASs. In support of this objective, the work in this project was organized around the seven tasks shown in Table 4.2. The outcome of this project was a prototype flying platform, sensors, algorithms and operational procedures which enable autonomous monitoring of traffic and highway infrastructures and relay information in real-time to remotely located decision makers.

The scope of this work did not include developing new and novel sensing or aerial platform technologies. Instead, it was to demonstrate the effectiveness and practicality of using RPVs or UAVs to monitor traffic and highway infrastructure. The scope of this work, therefore, was limited to modifying an existing aerial platform as required and to instrument it with proven technologies for imaging and geo-referencing. Stated differently, the focus of this work was to identify existing sensors, systems and miniature aerial platforms; show how they can be used to construct an aerial surveillance platform; and demonstrating the capabilities of such a platform.

It should be noted that the systems and procedures developed as part of this work are be dual-use technologies which have direct relevance to homeland security applications. Furthermore, it should also be noted that the final product of the work was a demonstration of traffic and highway infrastructure monitoring using UASs and not the equipment for accomplishing this function. Therefore, the hardware and software developed as part of this project was not designed to be put operational service by law enforcement or local government agencies. Instead, the systems developed will be a prototype of what will eventually become a "turn-key" solution to the problem of traffic and highway infras-

<table>
<thead>
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<th>Task</th>
<th>Duration/Months</th>
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Table 4.1: Work Time-Line
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<th>Task</th>
<th>Description</th>
<th>Duration</th>
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<tbody>
<tr>
<td>1</td>
<td>Develop the RPV Platform</td>
<td>4 Months</td>
</tr>
<tr>
<td>2</td>
<td>Sensor Payload/Suite Development</td>
<td>6 Months</td>
</tr>
<tr>
<td>3</td>
<td>Ground Station Development</td>
<td>9 Months</td>
</tr>
<tr>
<td>4</td>
<td>Operational Test of Integrated System</td>
<td>3 Months</td>
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<tr>
<td>5</td>
<td>Operational &amp; Test Procedure Development</td>
<td>11 Months</td>
</tr>
<tr>
<td>6</td>
<td>Validation Experiment</td>
<td>2 Months</td>
</tr>
<tr>
<td>7</td>
<td>Write Final Report</td>
<td>1 Months</td>
</tr>
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Table 4.2: List of Tasks

...tructure monitoring via RPVs and UAVs. It is expected that more work and effort will be required to convert the systems developed into a final product for operational use.

Except for Tasks #4, #6 and #7 all proceeded concurrently during the project. This is clearly shown in the work time-line shown in Table 4.1.

4.1 Project Budget

The total project budget was divided into the two categories: (1) Budget for purchase and fabrication of hardware and (2) Personnel salary and other expenses. At the end of the project on December 31, 2007, approximately $21 K of the portion allotted for equipment fabrication and hardware remained. These are funds that were set aside to purchase and fabricate an image processing, stabilizing and feature tracking system/software. These remaining funds are discussed later in the report in relation to recommended future work.
Chapter 5

Tasks And Outcomes

In what follows, a detailed description of each task and its associated outcome or deliverable is given. Along the way, we will also briefly discuss our findings regarding issues that need further study.

5.1 Task 1: Develop an Autonomous Aerial Platform

The objective of this task was to develop an aerial platform that is compact, robust and easy to operate. While it may have been possible to develop an aerial vehicle design that is unique to this specific project (and this was the case with a sister project discussed in [22]), it was deemed less risky (from a project schedule point of view) to purchase an existing aerial vehicle kit and modify it. Important constraints that led the selection of the kit and final modification were that the vehicle had to be compact (i.e., small in size and weight), stable in flight and easy to operate.

The first of these constraints (compactness of size and weight) originates from the fact that the aerial vehicle must be easy to move from location to location as dictated by the traffic monitoring functions at hand. Furthermore, the final users of this aerial vehicle will more than likely be government or law enforcement officials. Thus, this means that the aerial vehicle should be able to fit in vehicles used by law enforcement officials such as a squad car or a van.

The second constraint (stability of flight) resulted from the fact that one of the important payloads on such miniature aerial vehicles is an Electro-Optical (EO) camera. This is because one of the primary missions of these vehicles is that of being video-image gathering platform. Thus, the amount of video and image processing required to stabilize the images will be less if the camera is also relatively stable. Image stabilization and processing are issues that we believe warrant further examination and, thus, will be discussed in more detail at the end of the report.

The third constraint (ease of operation) originates from the fact that the utility of such device increases if it does not require specially trained personnel to operate it. Furthermore, the less complex it is to operate means that the potential for operational errors that can be hazardous (e.g., loss of control of the vehicle) will be minimized. This requirement is at the heart of the issues surrounding regulatory requirements for the operation of these vehicles.

5.1.1 Airframe and Powerplant Selection

In view of these design constraints, the final platform selected to meet all these requirements was a kit manufactured by Unicorn Wings [17]. The kit airplane is known as the Unicorn. This aerial
platform kit has been used in related projects at other universities including a very successful US Air Force sponsored project at Brigham Young University [18]. The Unicorn is shown in Figure 5.1 and it can be seen that it is a flying wing design. As shown in the photograph of Figure 5.2, it is easy to launch manually.

![Figure 5.1: Aerial Vehicle Unicorn.](image)

5.1.2 Avionics Selection

Central to autonomous or remote operation of an aerial vehicle is a Guidance, Navigation and Control (GNC) system. The GNC system generates high bandwidth information about the aerial vehicle’s navigation state vector. The navigation state vector consists of the position vector, velocity vector and three attitude angles (i.e., yaw, pitch and roll)

In the course of the project, it was determined that there was not a single off-the-shelf system that would address all the GNC system requirements. Thus, the aerial vehicle we designed used two off-the-shelf GNC systems: the MicroPilot MP2028 and the Microbotics Inc., MIDG II.

**MicroPilot Model MP2028**

The MicroPilot MP2028 is an integrated GNC system shown in Figure 5.3. That is, it incorporates the guidance, navigation and control functions in one unit. With the MicroPilot, the user defines a trajectory that the aerial vehicle will follow via a series of waypoints. Once these are programmed into the MicroPilot, the aerial vehicle will follow the trajectory using information generated by a navigation and attitude determination system based on the fusion of GPS and inertial sensors.

While the MicroPilot is an off-the-shelf GNC solution and was used extensively in the Unicorn for autonomous operations, there are some issues associated with using it in a fielded system. The primary
issue has to do with the fact that the software behind the GNC solution is proprietary and the user does not have access to it. Since the user does not have access to the internal workings of the MicroPilot, it is difficult to assess the level of safety and redundancy. Precisely quantifying the level of risk due to software performance, to a large extent, is dependent on the GNC algorithm’s ability to detect and isolate faults in real-time. Assessing a GNC system’s ability to do this is essential for certifying GNC systems. Thus, it was difficult to assess the overall risk and robustness of the system. This was addressed, in part, by the work done in Task 2. This involved developing an open-source GNC software algorithm suite.
Microbotics Inc. MIDG II

Shown in Figure 5.4, the MIDG II is an integrated GPS/Inertial Navigation System (INS) with an automatic pilot or control system extension which can be purchased separately. In this project we did not use the MIDG autopilot because the performance of MicroPilot controller was found to be satisfactory. The MicroPilot system was also less costly than the MIDG II-based system. However, the attitude solution provided by the MIDG II had higher accuracy and was more robust. This higher accuracy and robustness was required for the ground station interface software and geo-referencing.

![Figure 5.4: Microbotics MIDG II Integrated GPS/Inertial Navigator.](image)

The MIDG II generates a position, velocity and attitude solution by fusing the information derived from a triad of accelerometers, gyros and magnetometers with GPS. The result of this fusion is a relatively accurate and drift-free solution of position, velocity and attitude (orientation) of the aerial vehicle. However, the quality of the attitude solution is still considered marginal for precise geo-registering applications.

The architecture of the GNC system which features these two systems and was flown extensively in our flight tests is shown in Figure 5.5. Even though both systems were used simultaneously, only the MicroPilot was used required for guidance, navigation and control of the aerial vehicle. Ground station data visualization or operator interface software required the higher attitude accuracy afforded by the MIDG II.

To ensure that a failure in the control system does not result in a hazardous situation, the aerial vehicle was equipped with a fail-safe system. This system allows the ground operators to isolate the control system in case it fails or an anomalous condition is detected. Once the control system is isolated, the ground operators can manually fly the aerial vehicle to safety. This system is shown at the center of the schematic in Figure 5.5 labeled “Fail Safe System.” This component is there because the control system must possess a high level of reliability since a failure of the system leads to an uncontrolled aerial vehicle.
5.2 Task 2: Sensor Suite and Mission Payload Development

In order to accomplish the function of traffic and highway infrastructure monitoring, the miniature aerial vehicle had to be equipped with the appropriate mission sensor payload. For visual surveillance the mission payload is an Electro-Optical (EO) camera. For some law enforcement operations the EO camera may be replaced by an Infrared (IR) camera.

To support processing of the data collected from the mission sensor payload, the miniature vehicle must be equipped with a data-link modem. The GNC system generates information about the miniature vehicle’s state vector (position, velocity and orientation or attitude) which is used to aid in actively pointing these cameras at the right target. Alternately, in a passive mode of data gathering the navigation state vector is used for geo-referencing the images captured by the onboard camera (i.e. know the location and orientation of features in the captured image relative to some coordinate frame fixed to Earth) and, thereby, facilitate displaying them to the decision makers at the remote site. Finally, all the data collected by the aerial vehicle is transmitted to the ground station for visualization, decision making and archiving. The transmission of the data is accomplished using a radio-modem or data-link.

5.2.1 Mission Sensor Payload: EO Camera

In this project, the mission sensor payload was a video camera or an imaging system. The video imaging system consisted of two onboard cameras and associated electronics. The installation was such that the maximum coverage of the scene below the miniature aerial vehicle was be available at all times. Thus, the onboard cameras were be installed in the airframe as to provide the maximum Field of View (FOV). The video images captured by these cameras were transmitted in real-time to the ground station for visualization. The transmission of the video images was accomplished by using a pair of analog video transmitters.

The cameras and video transmitters were integrated into a camera pod or "blister" which can be...
easily attached or removed to the Unicorn aircraft. As a matter of fact, the camera (or mission sensor payload) pod is shown in Figure 5.6 attached to another airframe. When landing the Unicorn, the camera pod is the first point that comes into contact with the ground. As such, for strength, the pod was constructed from hard plastic.

![Camera Pod](image)

Figure 5.6: Camera Pod or "Blister" for Mounting Cameras on Miniature Aerial Vehicles.

### 5.2.2 Data Link Modem

Navigation data from the aerial vehicle are essential for the data visualization and operator interface. The programs for data visualization and operator interface that run on the ground station computer require the miniature aerial vehicle’s position, velocity and attitude information at a rate of no-less than 1 Hz. The ground station must also be able to reliably send data up to the miniature aerial vehicle to effect a manual override of the automatic pilot in case of a malfunction. These requirements drive the need for a data-link modem that is robust to data dropouts and has high data bandwidth.

In this project the data-link modem used was a MaxStream RF modem. These were 900 MHz RF modems. In our testing we found that these modems were able to transmit data reliably at a baud rate of up to 20 Kbps and distances up to 1 mile.
5.2.3 Open-Source GNC Software: MicroGear

As noted earlier, the GNC system must possess a high level of reliability since a failure of the system leads to an uncontrolled aerial vehicle. Thus, the GNC used in the Unicorn was equipped with a fail-safe system. This system allowed the ground operators to isolate the control system in case it fails or an anomalous condition is detected. Once the control system is isolated, the ground operators can manually fly the aerial vehicle to safety. The fail-safe system is described in more detail below. This, of course, is a solution suitable only for a prototype system. In a system that will eventually be fielded in a realistic operational setting, we cannot assume that the operators on the ground are trained to pilot aerial vehicles. Thus, to ensure that the public is not exposed to an unacceptable level of risk, either one of the following will have to be done:

1. A detailed analysis to show that the risk of failure in the control system due to hardware or software malfunctions is below some pre-defined threshold. This threshold is defined by the agency that will be responsible for certifying such aerial vehicles.

2. Design of back up systems to ensure that no single hardware or software malfunction will lead to failure will lead to situations with an unacceptable large level of risk.

It should be noted that the failures that need to be considered are not only those associated with the control system but also all other systems on which it relies such as the navigation and guidance systems. Designing potential hardware backup systems as well as analysis techniques for validating the GNC system risk is the topic of an on-going ITS institute sponsored research project. This project will be discussed in more detail later in the report when discussed proposed directions for future work.

In order to be able to perform detailed risk analysis, we developed an “open” GNC solution. This solution used software (which is now an open-source software) with an off-the-shelf flight control unit hardware. The system developed is called MicroGear and combines the flight simulation and visualization features of the open-source flight simulator FlightGear with the open sources GNC algorithm developed as part of this work.

The MicroGear software architecture is shown in Figure 5.7 and described below.

Guidance System

For autonomous operations, the user must define a geographic area or boundaries within which the aerial vehicle must fly. In the system developed for this project, this consisted of defining a series of waypoints. Waypoints are locations in space which, when connected in the appropriate sequence, define a path that a vehicle has to fly. The guidance system provides the interface by which the operator defines the waypoints. This is the input to the guidance algorithms as shown in Figure 5.7. The algorithms generate steering instructions that are used by the control system to guide the aerial vehicle along the path defined by the waypoints.

Navigation System

The navigation system determines the vehicle’s position, velocity and orientation. In the various GNC architectures we examined and flew, the sensor used for position and velocity determination was GPS. The reason for using GPS is obvious: GPS is a ubiquitous utility in modern navigation which, depending on the type of implementation used, is capable of generating position estimates
accurate to the meter- or centimeter-level. Other navigation systems (e.g., LORAN [20] or navigation grade Inertial Navigation Systems (INS) [21] without external aiding) cannot match this performance provided by GPS. In addition, GPS receivers are compact and have low power consumption. Thus, they are ideal for use in small aerial vehicles. GPS receivers capable of processing differential corrections and generating a navigation solution with accuracy on the order of a few meters are inexpensive and readily available.

Orientation (or attitude) determination is considered part of the navigation system. In the systems developed for this project, attitude determination was accomplished by combining (or fusing) the information from an Inertial Measurement Unit (IMU) with the information from one or all of the following sensors: GPS, magnetometers (solid state compass) and air data (air speed) sensor. The IMU consists of a triad of accelerometers and rate gyros to measure vehicle acceleration and rotation rates, respectively.

The aiding from the other sensors such as GPS or magnetometers is required because the attitude solution derived from an IMU will have drift errors. These drift errors can be unacceptably large (greater than 1 degree) unless highly accurate (and, thus, expensive) IMUs are used. However, IMUs that are capable of generating an attitude solution with accuracy on the order of half a degree are either too expensive (in excess of $60 K) or incompatible with miniature aerial vehicle operation. For example, the IMU used in the system described in [7] is one of the most accurate, high-end attitude determination system available today used in traffic management research similar to the application discussed here [21]. It weighs approximately 24 lbs, consumes 37.5 watts, costs approximately $100 K. Clearly, it is not suitable for use in inexpensive miniature aerial vehicle systems.

This unavailability of compact, accurate and inexpensive attitude determination systems is one of the reasons why a single “turn-key” solution for GNC of miniature aerial vehicles is not available. The schemes used for integrating the IMU information with that of GPS or the other sensors makes assumptions on the dynamics (or the nature of the motion) of the vehicle. Thus, the performance reported in specification sheets for these attitude determination systems may not be achievable in all
operational scenarios.

**Control System**

The control system is what sometimes is referred to as the "automatic pilot." It autonomously operates the aerial vehicle by moving the vehicle’s control surfaces and throttle. To do this, it continuously compares the information from the navigation system (i.e., information about the current location, speed and attitude of the aerial vehicle) against the guidance system output (i.e., information about where the aerial vehicle should be based on the pre-defined flight trajectory and waypoints). If there is a mismatch between the navigation solution and the desired guidance path, the control system operates the control surfaces and the throttle of the aerial vehicle to make sure that it remains on or close to the pre-defined trajectory.

![Crossbow MicroNav GNC Hardware](image)

Figure 5.8: Crossbow MicroNav GNC Hardware. The MicroGear Open-Source Software Used the MicroNav Sensors.

The hardware behind MicroGear is the Crossbow MicroNav. The Crossbow MicroNav provides a system which contains an inertial sensor suite, an air data system and a GPS receiver integrated into a package with a small form factor. Figure 5.8 shows the MicroNav which is compact unit containing all the hardware required for navigation, guidance and control. The user supplies the algorithms. This latter feature—an open source navigation, guidance and control algorithm suite—enabled us to modify our algorithms to suite our specific needs. That is, the user is able to modify the GNC software and tailor it to satisfy specific needs. Since the operational characteristics of small aerial vehicles can be very different from one model to the next, GNC software has to be tuned for each specific vehicle. Similarly, different missions require differently tuned GNC algorithms. For these reasons, the MicroNav represents a very attractive platform for miniature UAS systems. The MicroNav system is currently allowing us to perform detailed analysis on risk associated with potential software malfunctions as part of another ongoing ITS Institute research project. Performance of the MicroGear is discussed later in the report.
5.3 Task 3: Ground Station Development

The ground station is shown schematically in Figure 5.9. The major efforts under this task involved constructing the hardware required and developing the software that runs on the ground station. Each of these components (hardware and software) will be discussed separately in the paragraphs below.

Ground Station Hardware

The video and associated geo-referencing data transmitted from the aerial vehicle is received, processed and displayed by the ground station and its subsystems. At the ground station, data-link receivers with omni-directional antennas to receive the data from the aerial vehicle. The navigation, attitude and video data is processed by one of the ground station computer. The processing consists of assigning a GPS time tag and formatting the video and geo-referencing data for archiving. The processed video image is sent to the second ground station computer to be processed and then displayed to aid in real-time decision making. The video and geo-referencing data are both archived on the ground station computers. The archiving allows post-mission playback of the data. A photograph of the ground station that was depicted schematically in Figure 5.9 is shown in Figure 5.10.

Ground Station Software

The ground station software had three major functions. First, it archived video and GNC system data (aerial vehicle position, speed and attitude histories). Second, it provided a way to interact with the vehicle in real-time. That is, it allowed the operators on the ground to send commands such as waypoint changes to the aerial vehicle. Third, it presented data in real-time which enhanced situational awareness of the operators on the ground. The software used to interact with the aerial vehicle in real time was an off-the-shelf product supplied with the MicroPilot automatic pilot. Archiving of video data was similarly accomplished using an off-the-shelf software solution. The software used for the third function (enhanced situational awareness) was developed specifically for this project.

The software is part of the MicroGear software suite. MicroGear not only allows visualizing data for enhanced situational awareness (as will be discussed below) but also provides a means by which to design, tune and validate GNC algorithms written for the MicroNav GNC system (as discussed}
earlier). We will not discuss the latter functionality of MicroGear in this report as it is beyond the scope of this work. However, the use of the MicroGear software to enhance situational awareness is central to the project and will be discussed in some detail next.

MicroGear Data Visualization Software

MicroGear is an adaptation of the open source flight simulator known as FlightGear. In a nutshell, the MicroGear software generates a synthetic display on one of the ground station computers. The display depicts the view that would be seen by a hypothetical observer on the miniature aerial vehicle. The view displayed is similar to but not identical to the view generated by the onboard video camera. The camera provides a view of the actual scene below the aerial vehicle at the time of flight. The view generated by MicroGear is based on satellite imagery from a Geographic Information System (GIS) database. The GIS database information allows depicting roads, buildings, vegetation and other permanent or semi-permanent features. Given an accurate estimate of the vehicle’s (and, thus, camera) position coordinates, attitude and a GIS database, a virtual reality (or synthetic) image of what the camera should be seeing can be constructed.

Figures 5.11 and 5.12 show a comparison of the image from a video camera and a synthetic version of it generated by MicroGear. The photo is of the location where flight tests were conducted. It is known as Jensen Field and is located in Rosemount, Minnesota. Figure 5.11 is a snap-shot of a view captured by the onboard video camera. Figure 5.12 shows the synthetic image generated by MicroGear in flight over Jensen Field.

Because of attitude and position errors as well as field of view differences between the camera and
the virtual image, the camera captured and the synthetically generated scene may not match exactly. In this case, matching the two images, however, is just a matter of stretching and shifting the synthetically generated image to match the image captured by the camera. Another source of a mismatch between the two images is due to the fact that the satellite imagery being displayed in MicroGear will be taken at a time prior to the flight. If the time when the GIS information was taken is closer to the time of flight, this mismatch between the MicroGear display will be less. Figure 5.16 shows a snap-shot comparison between a video image and MicroGear’s depiction. Mismatches due to stretching/shifting have been corrected. However, a mismatch between the two (e.g., vegetation concentration) is due to the fact that the GIS database used pre-dates the date of the flight test.

The fact that the display provided by MicroGear is based on satellite imagery and not real-time video data is the key to enhanced situational awareness because:

1. In scenarios where images from EO cameras is degraded by environmental factors such as fog, low-lighting (night time operations), smoke, haze, etc, the live video broadcast to the ground station from the aerial vehicle may not provide any useful information. However, since the MicroGear display is based on imagery not affected by these environmental factors, it will provide continued situational awareness such that the aerial vehicle is operated in a safe manner away from structures, buildings, etc.

2. Non-physical features can be incorporated easily into the display. For example, Figure 5.14
Figure 5.12: MicroGear’s Depiction of the Screen Capture Shown in Figure 5.11. Flight Instruments Showing Speed, Altitude, etc are Shown at the Bottom of the Display.

Figure 5.13: Side by Side Comparison of Live Video and a MicroGear Generated Display.

shows the boundaries of a Class B airspace displayed. This provides additional situational awareness to the operators of where to and not to fly the aerial vehicle.

Vehicle navigation state vector (position, history and attitude) are inputs to the MicroGear display. Thus, MicroGear also provides a method for archiving this data.
5.4 Task 4, 5 and 6: Testing and Validation of System

The objective of Tasks 4 was to validate whether the software and hardware developed and assembled for the overall system functioned properly. The objective of Task 5 was to develop operational procedures that were consistent with the current Federal Aviation Regulations (FARs). The object of Task 6 was to validate the entire system in an operational setting. Thus, in what follows we will discuss Tasks 5 and Task 6 only; the fact that the system was used in final demonstration is an indication that Task 4 was successfully completed.

The final validation test consisted of fusing the live video information coming from the miniature aerial vehicle with information from a GIS database in real-time and presenting that information on the ground station display. As simple as this test appears, it validates that all the algorithms and systems developed are working properly.

Two separate validation tests were conducted. In the first series of tests the Unicorn with the off-the-shelf GNC system was used. In the second series of tests, the MicroGear GNC system was tested. The tests included flights with the Unicorn and another larger aerial vehicle that was used as a sensor prototype system (a Sig Rascal). In this test, a series of waypoints were defined to simulate an operation where the miniature aerial vehicle was loitering over an incident (e.g., the I-35 bridge collapse). The aircraft was left alone to continue loitering and broadcasting live video images. The results were also integrated into the ground operating station software and displayed in a way to enhance the ground operators’ situational awareness. The resulting ground track is shown in Figure 5.15. This is a "bird-eyes” view of the aircraft flying. A three-dimensional version of Figure 5.15 is shown in Figure
Figure 5.15: Ground Track of an Autonomous Flight Enabled by MicroGear.

5.16. The series of "T" markers show prior positions and attitudes of the miniature aerial vehicles. The "T" can be imagined to be the aircraft’s wing and vertical tail. The display is a compact representation of both attitude and position history.
Figure 5.16: MicroGear Depiction of the Trajectory Shown in Figure 5.15.
Chapter 6

Summary

In this report we have described the initiative sponsored by ITS Institute, MnDOT and SRF to develop Unmanned Aerial Systems (UAS) for the application of surveillance in support of transportation infrastructure management and security. The work had two overarching objectives. First, it was to demonstrate the use of a UAS to autonomously monitor highways and relay information about traffic flow and traffic incidents, in real-time, to remotely located decision makers. This was to be accomplished by using "turn key" or "off-the-shelf" technologies. A miniature hand launched vehicle equipped with an "off-the-shelf" GNC suite was developed to demonstrate this objective. The second objective of the work was develop the capabilities required to investigate the technical and operational issues associated with using Uninhabited Aerial Systems (UASs) or for traffic monitoring and management applications.

The biggest challenge is certification of these vehicles. This requires, in part, a complete understanding of the GNC solutions used in each application and being able to perform detailed risk analysis on them. To this end, an open source GNC solution based on the MicroNav was developed. The complete transparency of the algorithms allows us to investigate issues associated with reliability and robustness. The algorithms and systems developed were validated in a series of flight tests.
Chapter 7

Future Research

The use of UAS will lead to changes in the methods used for gathering and processing information about traffic conditions, transportation facilities and infrastructure. It can potentially affect the strategic planning process as well as real-time management of traffic and highway infrastructures. By facilitating the monitoring of both operational traffic and of security related parameters, they serve as an example of a dual use technology. This utility will increase if vehicle cohorts and traffic parameters useful to traffic management can be determined. This will require that the UAS have the ability to geo-register images captured from an onboard video camera. This, in turn, will require additional work into two areas: (1) Image processing, stabilizing and feature tracking (2) GPS-based attitude determination.

7.1 Image Processing, Stabilizing and Feature Tracking

In the initial proposal that written to support this work, a task to develop a system which allows geo-registering images was included. However, in the process of this investigation it was concluded that “off the shelf” technology for accomplishing this was not readily available. In particular, inexpensive software packages that allow geo-registering images, were not readily available. Furthermore, the geo-registering problem requires that accurate vehicle attitude be available. Thus, this part of the project was not conducted and the associated $25,000 allotted for it was not used. It appears that solutions for doing both (geo-registering and accurate attitude determination) are now available or close to being available. Thus, we propose to continue this work in this area is warranted.

7.2 GPS Attitude Determination

As noted earlier, when this project was initially conceived, it was decided that a GPS attitude determination system be developed and used in the GNC system. This is a relatively immature technology and unanticipated challenges in its development were encountered. For the sake of minimizing schedule risk, we opted for alternative attitude determination systems in the form of the MP2028 and MIDG II. However, in parallel, the work on the GPS attitude determination system has continued. At this point in time, the technical issues that were problematic have been resolved. Thus, we believe it would be beneficial to continue development and finalizing the GPS-based attitude determination system. This is particularly beneficial in view of the fact that the attitude solution offered by this system
is more accurate than most of the off-the-shelf solutions available today (including the ones we used in this work) and is central to the geo-registering capability.

Related to these two efforts, there is ongoing work (sponsored by the ITS Institute) concerned with developing and demonstrating a systematic methodology for evaluating whether the operational concept of using multiple UAS to monitor vehicle states and other useful traffic management parameters meets safety requirements established by regulation. The methodology proposed involves identifying hazards associated with the concept of operation and quantifying the likelihood of their occurrence. For hazards where the likelihood of occurrence is judged to be too large, risk mitigation strategies will be developed. This methodology will be a useful tool for establishing certification standards by federal and state agencies responsible for the safe operation of UASs. It will also be a useful tool for designers of UASs and associated systems because it can be used to map operational requirements (e.g., system reliability, required accuracy on vehicle location and velocity estimation, etc.) into hardware specifications. Operational procedure designers can also use it to determine the required operator qualifications for this given concept of operation. The work associated with development of the MicroGear GNC software is integral to this effort.
References


