

Development of an Autonomous Tactical Reconnaissance Platform

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Abstract

A man-portable, autonomously controlled aerial surveillance platform has been developed. The ultimate goal is to provide a method for obtaining remote sensing data using an inexpensive, expendable device. The Autonomous Tactical Reconnaissance Platform (ATRP) consists of a standard parafoil that carries an instrumentation payload for autonomous flight and remote sensing capabilities for both military and civilian applications. The baseline design is for a device weighing less than 1.5 lbs. that is launched to an altitude of 1000 ft, where it deploys and flies a user selected program of autonomous flight maneuvers for several minutes. Telemetry from the ATRP provides the user with real time output from onboard sensor instrumentation.

An autonomous, fuzzy logic flight controller was developed to pilot the ATRP. A fuzzy logic architecture was optimized over a range of simulated flight conditions. The flight control algorithm provided a simple yet robust means of controlling the vehicle, thus enabling use of low cost, light weight components. Prior to launch the user selects one of a finite set of pre-programmed flight scenarios. After launch and deployment, the autonomous controller executes the pre-selected program of flight maneuvers as it glides in the descent phase.

A 4-ft tall rocket was designed and built to carry the 6-ft wingspan parafoil and electronics package. Flight tests proved the launch system could successfully deploy the parafoil and activate the autonomous flight controller. The rocket was launched to altitudes above 500 ft allowing for up to one minute of flight time for the parafoil.

Introduction

The ATRP device is a parafoil carrying a small payload that is instrumented for autonomous flight and remote sensing capabilities. A parafoil is a flying wing made of some flexible material, supported by lines that maintain its shape by virtue of the air flowing over and through it. The purpose of this project is to prototype

a system that can be used as a personal reconnaissance device. The ATRP has many military and civilian uses that are not adequately addressed by remote sensing systems currently available.

Reconnaissance data from various sources have proven to be a significant contributor to the success of most military campaigns, particularly in recent years.

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Today, the military employs a number of reconnaissance assets including satellites, manned aircraft, unmanned aircraft and human infiltration. These systems provide vital information to commanders at home and in the field, however they have limitation when it comes to supporting the individual soldier in real-time, hostile environments.

The vertical launch capability of the ATRP makes it unique among current micro-flyer concepts. This capability would be extremely valuable in rugged or jungle terrain and during nighttime operations. An infrared and/or visual sensor aboard the ATRP would pinpoint enemy location and numbers during such exercises. The ATRP provides the soldier with a close range, real-time view of the immediate surroundings.

The ATRP is designed to provide personnel in the field with a means of expanding their knowledge of the near environment in a safe, timely and cost effective manner. The ATRP is launched to low altitude (typically <1000 feet) and then flies a pre-selected course while transmitting sensor data to the user on the ground. During flight, the device is fully autonomous allowing the user to direct their concentration on the sensor data (i.e. IR imaging, visual imaging, radio communication and potentially laser designation) being communicated to a hand held receiving device. The user can select one of several pre-programmed flight patterns for the device to follow and launch, all in a matter of seconds.

One of the non-military applications for the ATRP is to provide inexpensive and good quality remote sensing data to farmers and land management professionals. A number of studies have

shown the value of remote sensing data in discovering areas in fields where crops are under stress due to disease, lack of nutrients or pests [1,2]. Current collection methods such as satellites and manned aircraft are expensive, geographically imprecise, and frequently unavailable at critical times in the growing season. The ATRP, equipped with a Global Positioning System and the appropriate sensors overcomes of these obstacles and allows farmers to perform a more personalized evaluation.

A parafoil design was chosen because it has several key advantages over rigid structure alternatives. A parafoil is lightweight, easily compacted and deployed, and very stable in flight. An autonomous, fuzzy logic flight controller pilots the parafoil for the ATRP. After launch and deployment, the autonomous controller executes the pre-selected program of flight maneuvers as it glides in the descent phase. A fuzzy logic control method is employed because of advantages it has in fault tolerance and graceful response to missing or noisy sensor input [3 – 6].

Alternative launch mechanisms (e.g. compressed air launch, artillery shell, tethered launch and deploy) may prove to be even more compact than the current rocket launched design. However, a rocket length of 3 feet or less should prove to be manageable for one person to carry even in rugged terrain. The need for a mobile system dictates various other constraints such as system weight, rocket motor size, parafoil sizing, and maximum altitude of flight and deploy.

The ATRP and its launch mechanism are man-portable, with set-up and launch operations achieved in a matter of

seconds. The ATRP is intended to be an inexpensive, expendable device, suitable for a wide variety of mission scenarios. The technology used in the ATRP is commercial-off-the-shelf (COTS), which is easily acquirable and inexpensive to manufacture.

Rocket Design

A conventional 4-ft tall model rocket with a 4 inch diameter was built as the launch platform. The body was made of phenolic tubing, and contained a motor mount and four fins. The hollow ogive shaped nosecone left room for the electronics package to be mounted inside. A standard motor burnout delayed ejection charge was used to separate the nose from the rocket body and release the parafoil. The main body of the rocket came down separate from the parafoil under a second small parachute. Before launch, the rocket weighed just under 7 lbs.

Commercially available solid rocket motors were purchased and used for flight testing. These motors were sized to allow the rocket reach to apogee and deploy the parafoil at an altitude of between 500 and 1500 ft., depending on the goals of each particular test flight.

Prior experience with a much larger rocket and parafoil demonstrated that the parafoil was relatively stable and easy to fly in radio control mode. However, the flight performance and load carrying capacity of the much smaller parafoil needed examination. The first parafoil purchased for this project was a commercially available kite, pictured in Figure 1 during early ground test evaluation [7].

Although the kite flew well tethered, the geometry of the control lines made free flight more difficult. When flown as a kite, these control lines are spaced about 2 feet apart up near the kite body as shown in Figure 1. The separation of control lines was necessary for stable flight, so a mechanism had to be constructed to separate these lines after the parafoil had been deployed from the rocket. This was accomplished using two attached rods with a spring loaded core carried aloft on the outside surface of the rocket. During deploy, the rods straightened at the bend and the core rod was driven through the joint to provide a rigid structure.



Figure 1 - Early Ground Testing of a Commercial Kite Parafoil

It soon became apparent that there were several drawbacks with the separator rod and ultimately, it was determined that a replacement parafoil would be a better solution.

The search for a new parafoil resulted in the purchase of a radio controlled powered parafoil [8]. This product consists of a small radio controlled, gas powered engine that is suspended below a parafoil canopy. The gas motor was not

used for this project, but the parafoil proved to be far superior to the kite model in several important respects. The new parafoil was designed for free flight and therefore had the correct line lengths to give the proper angle of attack while flying. This model also had fewer lines attached to the parafoil, thus reducing the possibility of tangles. It also was designed for the control lines to angle much closer together, which reduced the length of the separator rod needed for stable flight. This new paraplane with the gas engine is shown below in Figure 2.



Figure 2 - Paraplane and Cart

The much smaller separation distance required for the control lines made it possible to launch the rocket with the separator rod already deployed. The rocket with the separator rod in position is pictured in Figure 3. Although drag on the rocket increases with the external rod, this design proved to be very reliable in deploying properly.

Another improvement made from early designs was the significant reduction in weight achieved by using lighter materials and construction techniques. The lighter rocket allowed for the use of

less powerful rocket motors resulting in a much less restricted launch regimen. Launches could be performed in virtually any open field, which allowed for an increase in the frequency of launches and the development pace.



Figure 3 - Improved Parafoil Control Design (note the small control line separator mounted sideways through the rocket)

Electronic Hardware

The control function is provided by a Motorola M68HC11 microcontroller on a Handy Board with a system clock speed of 2 MHz. This unit also has 32 kilobytes of battery backed RAM memory for user programming. For this project, the optional extension, the Expansion Board, was also purchased. The Handy Board/Expansion Board is equipped with one RS-232 serial port, 21 analog input ports, 8 digital input ports, 9 digital output ports and 6 servo motor output ports. Programming is performed on a PC and the resulting code is downloaded over the RS-232 port via a separate

Interface/Charger board to the Handy Board micro controller.

A Precision Navigation Inc. TCM2-50 digital compass was used to provide directional input to the Handy Board. An RS-232 channel was also needed for the Handy Board to communicate with this compass. Fortunately the Handy Board manufacturers provide a small amount of board space to accommodate additional, user developed, circuitry. A circuit design incorporating a Maxim MAX232CPE interface chip and associated electronics was developed and soldered into place on the board by project team members. This circuitry was configured to allow the Handy Board to communicate with the compass. The Handy Board is a general purpose controller board with many extra features (and some limitations) that were not required for this project. As the ATRP design matures it is expected that the Handy Board would be replaced by a more efficient, custom design.

The TCM2-50 compass was the single most expensive electronics component purchased for this project. The TCM2-50 spec sheet claims an accuracy of $\pm 1.5^\circ$ RMS even when tilted from level by as much as $\pm 50^\circ$.

The accuracy of the compass even when tilted to extreme angles was considered very important during the initial design phase. There was some uncertainty in how much tilt motion would be experienced by the instrument package during flight. Video of subsequent parafoil flight tests suggests that these tilt angles are not as severe as expected. Currently, cheaper compasses with only limited tilt compensation capability, are being tested and compared to the performance of the TCM2-50.

An Analog Devices, Inc. ADXL190 accelerometer was also included in the electronics package. Early in the ATRP design, the accelerometer was considered as a means of establishing when the deployment charge had been fired. This concept was discarded and a simple magnetic switch located at the separation seam was used to signal that the deploy charge had fired.

Assembling the various components into a rugged package that would fit within the confines of the rocket body was a subject of significant development effort. The eventual package design consisted of several lightweight bulkheads joined together by 4 threaded metal rods. The original steel joining rods had to be replaced with brass when it was determined that the steel interfered with the magnetic compass calibration. Figure 4 shows the electronics package prior to insertion in the rocket.

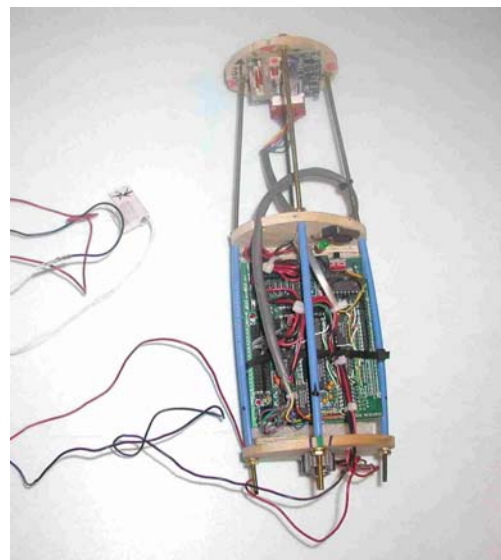


Figure 4 - The electronics package prior to insertion into the rocket nosecone

Development of Fuzzy Logic Algorithm

A fuzzy logic control algorithm provides the decision making strategy for the ATRP. There are a number of other excellent control methodologies available and indeed proportional integral derivative (PID) algorithms of one type or another are used in 90% of current controllers. PID controllers have been enormously successful in a variety of applications and in most cases have proven to be both very efficient and accurate. However, the fuzzy logic controller does have distinct advantages for this particular application.

Attributes of fuzzy logic that make it appealing for this project are the ability to model nonlinear functions, robustness in the face of imprecise input and ease of code generation. Fuzzy logic algorithms are intuitively easy to understand and allow the user to encapsulate the experience of experts in an efficient manner. Fuzzy logic controllers are seeing much more widespread use in a wide range of industrial and consumer devices (i.e. washing machines, automobiles and microwave ovens).

The process of developing the fuzzy logic architecture began by determining what inputs would be needed to provide directional control of the ATRP. The next step was to determine what instruments would be used to provide the inputs. A number of quantifiable factors including cost, weight, size and instrument accuracy as well as more subjective factors such as ease of use and compatibility were part of the decision process. Ultimately a digital compass was selected to provide heading information in this first prototype effort.

The compass provides heading data with respect to true magnetic North and by differentiating this heading with respect to time, angular velocity is determined. These two parameters, absolute heading and angular velocity, were considered to be the minimum inputs necessary for directional control. A third input, angular acceleration, was also considered with many simulation runs performed to determine whether it would be required. There was a trade-off in including angular acceleration between improved directional performance versus processing speed and memory requirements and ultimately it was determined to be unnecessary to include it.

The next step in the process was to develop membership functions for the three inputs (heading, angular velocity and angular acceleration) and the one output (control line pull). The magnitude and sign of the output would determine the magnitude and direction of the pull on the control lines, which in turn determined the magnitude and direction of turns of the ATRP.

The design of the inputs and the output membership functions have the freedom to assume different arrangements, shapes and number of functions, thus providing an infinite variety of possible combinations. This flexibility is something of a double-edged sword in that it provides the means of optimizing the system but also makes the optimization process a very daunting task.

After an initial number and shape are determined for the membership functions of each input and output, rules are developed to relate the various potential input scenarios to the desired output

result. The maximum number of possible unique rules is calculated by multiplying the number of membership functions for each input. For instance if there are 5 membership functions for heading and 5 for angular velocity, then there will be $5 \times 5 = 25$ possible, unambiguous rules. By adding a third input with 5 membership functions, such as angular acceleration, the number of possible rules increases to 125. The potential for the rule base to expand rapidly makes it imperative to judiciously limit the number of input parameters.

In practice, the number of rules can be trimmed by reducing the number of membership functions for each input. A further reduction in the rule base can be achieved by eliminating rules that will never be activated or “fired” in the real world mission of the ATRP. Additional rule pruning can be achieved by eliminating rules that are redundant. Still there is a great danger of rapidly expanding the rule base by adding input parameters, described in the literature as the “curse of dimensionality”.

The MATLAB Fuzzy Logic Toolbox was used to develop the fuzzy control algorithm [9]. One major advantage of using the MATLAB Fuzzy Logic Toolbox is that it can be directly linked to the Matlab Simulink software to provide a full simulation of an ATRP flight. It is this simulation capability that made it possible to refine the control software and thus drastically reduce the number of test flights necessary for control optimization.

Flight Simulation and Fuzzy Algorithm Optimization

The parafoil design is inherently a very simple and stable flight vehicle. Directional control is affected by pulling

on one of two control lines connected to either side of the parafoil wing. One simplifying assumption made in the simulations was that the parafoil flies at a constant speed with no need for pitch axis control. This assumption is at least valid to a first degree of approximation and was not a limiting factor in optimizing the control algorithm.

It was not the task of the simulation to optimize the aerodynamic qualities of the parafoil platform and therefore only a rough degree verisimilitude was necessary to achieve our goals for the simulation. The goals were to determine the minimum number of sensor inputs to achieve satisfactory, stable control, determine the most effective sensor inputs for achieving control, optimize various fuzzy logic components (i.e. membership functions, rule base, etc.) under ideal conditions and test/re-optimize the algorithm under simulated sensor and environmental sources of imprecision (i.e. sensor electronic noise, wind gust disturbance, wind drift). Figure 5 shows a block diagram of the various software components used in the simulation and optimization process.

The simulation blocks shown in green in Figure 5 represent functions that occur in hardware and/or software on the parafoil. The yellow block contains simulations of parafoil interactions with the environment and the blue block provides output for the user. Following the block diagram above, the simulation begins with the selection of a desired flight scenario. The difference between the desired and actual heading along with the first derivative of this difference is supplied to the fuzzy logic controller. The controller uses these two inputs to produce a control line pull

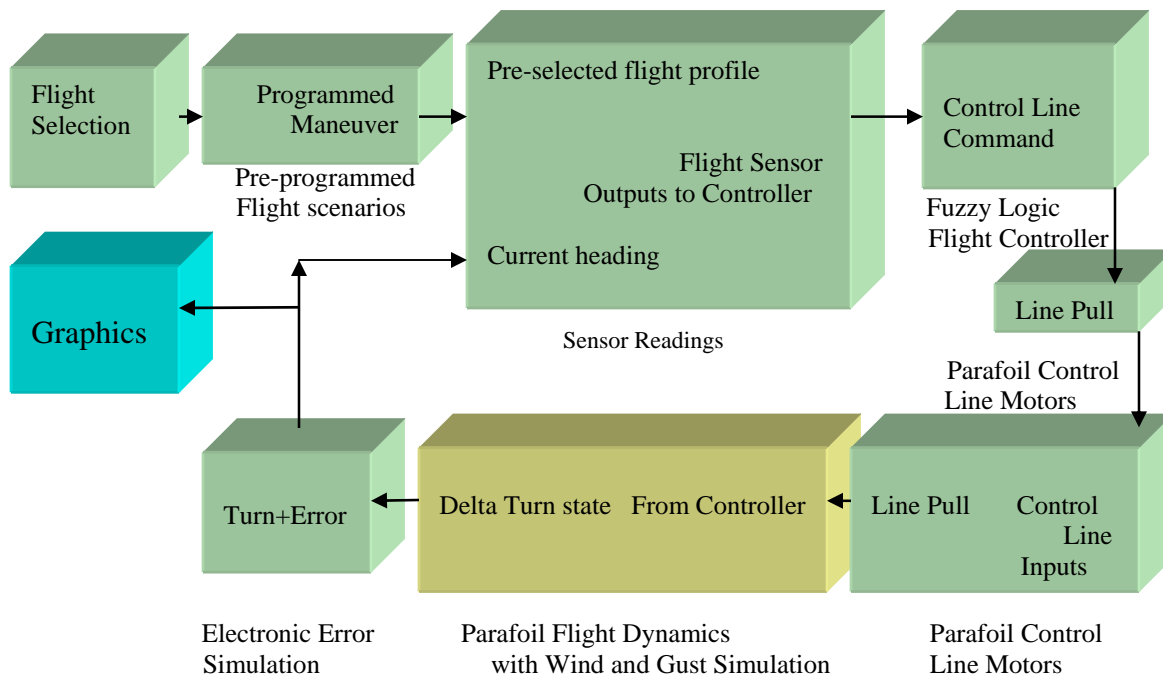


Figure 5 - Parafoil Flight Simulation/ Optimization Block Diagram

command. The effect of the control line pull command on the aerodynamic performance of the parafoil is computed and an incremental parafoil heading vector is determined. Any simulated electronic errors are combined with the heading vector to complete the loop and to provide input to the graphical output module. The simulation runs for the length of a single simulated parafoil flight.

Various authors have attacked the optimization problem using genetic algorithms, neural networks and other even more exotic methods. These methods tend to be complicated and fragile. A more brute force approach was chosen which required running a large number of simulations and comparing graphs of a few key outputs from each run. This approach was labor intensive and somewhat subjective, but it didn't require a lot of time or money in development, which were both key constraints in this project.

Ultimately it was determined that a continuously updated compass heading and a delta compass heading, or angular velocity, would provide sufficient input to the fuzzy controller for the ATRP to accomplish its mission. One additional input, angular acceleration, was considered and provided improved results in certain scenarios. However, the price in processing speed, complexity, and memory requirements did not justify the modest improvement gained by adding this input.

Initial Optimization runs were performed assuming ideal conditions. Later analysis included error sources such as electronic noise, wind gusts, and random heading after initial deploy. The majority of the analysis effort was devoted to evaluating various fuzzy architectures under these non-ideal conditions. Thus the fuzzy logic architecture required optimization over a range of simulated flight conditions.

Flight Tests

A series of flight tests were performed to test the rocket design, the deploy mechanism, and gather information about the aerodynamic characteristics of the parafoil that was then used to optimize the flight controller. A standard motor burnout delayed ejection charge was used in conjunction with a piston to separate the nose from the rocket body and release the parafoil. The rocket was launched on commercially available solid rocket motors of varying sizes depending on vehicle weight, to allow the rocket to reach apogee at an acceptable test altitude between 500 and 1000 ft.

In the initial test flights, the parafoil was controlled from the ground by means of a radio control mechanism designed and built for this project. The launch of the rocket was invariably perfect, however, there were problems encountered during the deploy event. Parafoil lines were often getting tangled or broken during deploy, resulting in an uncontrollable descent. Incremental improvements were made in the design, but it became apparent that a new approach would be required to achieve a high percentage of successful deploy and flight events. The solution was to use a different parafoil model that had fewer support lines and did not require the deployment of a control line separator rod.

The rocket design was also overhauled to create a new vehicle that was much lighter and could be launched to the required altitude using a much smaller motor. The very first launch of this new design resulted in an unqualified success in launch, deploy and radio controlled parafoil flight and landing.

A series of flights under autonomous control were then performed at Camp

Roberts Army base. The first flight, shown in Figure 6 just after launch, had a successful liftoff and ascent, however, the delay charge was too long and deployment occurred 3-4 seconds late. The late deploy event occurred as the rocket was well into its descent and at high speed. The stress of the high speed deploy of the parafoil caused one of the support line attachment points on the payload section to fail. The lack of support lines on one side made it impossible for the autonomous controller to fly the parafoil during the rest of the descent. Despite the resulting hard landing, the electronics package survived and data from the flight was down loaded to computers in the laboratory.



Figure 6 – Launch of Rocket with Parafoil

In the next launch, deploy was again somewhat late and a support line was looped over the top of the parafoil on one side. However, the fuzzy logic controller was able to compensate for these problems and was able to follow the desired flight path albeit with significant oscillations. In some respects it was satisfying to observe that the controller could perform so well under the deploy handicaps encountered on this flight.

The third launch again resulted in reduced flight time due to late deployment of the parafoil. However, the autonomous flight controller commands did function and valuable data was stored and downloaded from the electronics. The controller output showed that preprogrammed commands were executed to fly the parafoil in a straight out and return flight path. Continued flight testing will provide demonstration of the complete autonomous path.

Conclusions and Recommendations

The successful completion of the Autonomous Tactical Reconnaissance Platform (ATRP) project has produced a prototype, rocket launched parafoil capable of autonomous flight. The rocket based launch mechanism flew a series of test flights that optimized the deployment of the parafoil and its response to commands from the flight controller. Flight times were approximately one minute from altitudes between 500 and 1000 ft.

This project has shown that a fuzzy logic algorithm can provide the means for autonomous control of a parafoil in flight. The fuzzy logic control software was relatively simple to construct and proved to be both robust and forgiving of noisy inputs in simulations and test flights. These attributes made it ideal in an application where a major goal was to keep total product costs and system complexity to a minimum.

The parafoil and electronics package was an extremely rugged system. Flight test landings occurred in muddy fields and hard top roads without ever sustaining damage to either the parafoil or the electronics. The ATRP should have a much greater mean time between failure (MTBF) in

comparison to conventional fixed wing or rotorcraft systems.

The Matlab/Simulink software suite proved to be a powerful tool for developing and simulating the flight system. The Matlab Fuzzy Logic Toolbox was also very helpful in the development of fuzzy membership functions and production rules. Snippets of code in the C programming language were freely available from various internet sources, which made the software development task much less formidable.

There are a number of applications where the ATRP would provide a unique capability that is not adequately satisfied by other devices currently available. The ATRP is superior in terms of cost, ruggedness/durability, ease of use, portability, time to activate and reusability when compared with competing technologies in a variety of mission scenarios.

There are a number of military uses for the ATRP other than the baseline scenario described in this paper. Other potential military applications include airdrop guidance, battle damage assessment, and communications enhancement in rugged terrain. Civilian applications include; an aid in search and rescue efforts, evaluating plant health by farmers and land management workers, and as a communications and observation device for forestry fire fighting crews.

Future improvements will include incorporating the new technologies necessary to field a system ready for operational activity. The size and weight of the prototype system electronics and motor control package can be reduced by using more basic electronic elements in the design, a lighter and more efficient motor

and battery and lighter instrument packaging.

Other enhancements that will be incorporated are collision avoidance sensors, and a remote sensing device (e.g. IR camera) with telemetry transmitted to a ground station. The remote sensing device will communicate to a handheld wireless device with the user on the ground in real-time. In addition, a simplified launch mechanism such as compressed air could be used. The ATRP would also be enhanced with a tethered flight mode when long dwell times are required for communications and surveillance.

It is also possible to significantly increase parafoil flight performance by adopting a technique that involves dynamically changing the parafoil geometry while in flight [10]. It has been demonstrated that decreasing the span allows for faster flight without significant loss of L/D or glide ratio. The optimum parafoil geometry would be regulated throughout the flight by the onboard fuzzy logic controller.

The ATRP appears to have the potential for improving efficiency in both military and civilian applications with a very favorable cost/benefit ratio. The authors would like to thank the Office of Naval Research and Cal Poly for their support of this effort.

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