

## Griffon: A Man-Portable Hybrid UGV/UAV

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### ABSTRACT

**Purpose:** To demonstrate proof-of-concept of the Griffon man-portable hybrid UGV/UAV based on the iRobot PackBot.

**Design/methodology/approach:** We developed the Griffon Air Mobility System (AMS) consisting of a gasoline-powered propeller engine, a steerable parafoil, and a radio-controlled servo system. We integrated the AMS with a PackBot prototype, and we conducted ground and flight tests to validate this concept.

**Findings:** The Griffon prototype was capable of remote-controlled takeoff, flight, and landing. The Griffon achieved speeds of over 20 mph and altitudes of up to 200 feet.

**Research limitations/implications:** We demonstrated the feasibility of developing a man-portable hybrid UGV/UAV. Future work may explore the possibilities for teleoperated, semi-autonomous, and fully autonomous control using the Griffon concept. The parafoil wing limits the usability of this vehicle in windy conditions, but this could be addressed using a lightweight fixed wing instead.

**Practical implications:** Man-portable hybrid UGV/UAVs may be used by the military to perform reconnaissance and strike missions in urban environments, and by civilian teams to conduct search-and-rescue operations in hazardous terrain.

**Originality/value:** This research provides the first demonstration of a man-portable unmanned vehicle capable of both flight and ground locomotion, and it does so using a combat-tested UGV platform.

**Keywords:** Mobile robotics, UGV, UAV, urban combat

**Category:** Research paper

## INTRODUCTION

Unmanned aerial vehicles (UAVs), such as the Predator, have demonstrated their ability to aid warfighters in the current conflicts in Afghanistan and Iraq – both for reconnaissance and surveillance and for direct action against the enemy (i.e. Hellfire missiles). Unmanned ground vehicles (UGVs) have been successfully deployed for reconnaissance operations in both Afghanistan and Iraq. UAVs and UGVs are key elements in the design of the Objective Force as part of the Future Combat Systems initiative.

UAVs provide an operator with the ability to rapidly arrive at a site of interest, reconnoiter the area from above, and (in the case of the armed Predator) deliver a lethal payload to any exposed target. However, UAVs lack the ability to observe or attack targets that are concealed inside structures, such as caves or buildings. In contrast, UGVs have the capability to enter structures, search for targets, and examine these targets at close range (using video transmission). However, UGVs are much slower than UAVs, have limited range, and have less capability to cross very rough terrain. In many situations, what is needed is an unmanned vehicle that combines the strengths of UAVs and UGVs.

Griffon is a man-portable UAV/UGV hybrid designed to perform reconnaissance, surveillance, and payload delivery. Griffon was funded by the U.S. Army Tank-automotive and Armaments Command (TACOM) Armaments Research, Development, and Engineering Center (ARDEC) as a Phase I Small-Business Innovation Research (SBIR) project. Griffon is based on the iRobot PackBot platform, a rugged, man-portable, all-weather, all-terrain robot platform that is currently being used in military operations in both Afghanistan and Iraq. PackBot is available as a commercial product from iRobot Corporation.

Griffon adds an Air Mobility System (AMS) to the PackBot. This system includes a powered parafoil with a small, gasoline-powered motor mounted on the PackBot chassis. The PackBot control system steers the parafoil and controls the speed of the motor. The entire system is designed to be transportable by a single soldier.

Griffon also has commercial applications in civilian search and rescue in rough terrain. Griffon's flight capability will enable it to fly over lakes, mountains, and other potential obstacles to ground movement. When Griffon finds a victim, it will be able to land, deliver medical aid, and allow the victim to communicate with rescuers.

Many of Griffon's capabilities are already implemented on the PackBot, including real-time video and audio, teleoperated control, and autonomous ground navigation to GPS waypoints. In Phase I of this project, our objective was to prove the Griffon concept using a radio-controlled (R/C) prototype. In May and June of 2003, we conducted flight tests of this proof-of-concept demonstrator using a COTS parafoil, engine, and R/C servo control system. The purpose of the R/C demonstrator was to:

- Confirm that the selected AMS parafoil wing provides sufficient lift for desired flight characteristics with a PackBot payload.
- Confirm that the selected AMS gasoline engine provides sufficient thrust for desired flight characteristics with a PackBot payload.
- Confirm the flight stability of the integrated AMS and PackBot.
- Evaluate AMS flight characteristics under R/C servo control.

In the final flight demonstration, we launched the Griffon prototype on three separate flights, with the final flight reaching altitudes of 150-200 feet and ending in a controlled landing and smooth transition to ground motion. These test flights validated the Griffon UAV/UGV concept and laid the foundation for the development of a fully-operational Griffon prototype in subsequent work should funding become available.

## PACKBOT UGV

Griffon is a UAV/UGV hybrid whose components include a PackBot UGV, a parafoil, and a gas-powered engine with a propeller. We selected the PackBot because of its capability as a highly-robust, all-weather, all-terrain, man-portable mobile robot (Yamauchi, 2004).

PackBot was developed under the DARPA Tactical Mobile Robotics program (contract F04701-01-C-0018). PackBot is equipped with two main treads, used for locomotion, and two articulated flippers with treads that are used to climb over obstacles. PackBot can travel at sustained speeds of up to 4.5 mph, and burst speeds of up to 9 mph. On a full set of batteries, PackBot can drive at 4.5 mph continuously for 8 hours, for a total range of 36 miles. Standing still, PackBot can run its computer and sensor package for 36 hours.

PackBot is 27 inches long, 16 inches wide, and 7 inches tall, and weighs 40 pounds. All of a PackBot's electronics are enclosed in a compact, hardened enclosure. These electronics include a 700 MHz mobile Pentium III with 256 MB SDRAM, a 300 MB compact flash memory storage device, and a 2.4 GHz 802.11b radio Ethernet. Each PackBot can withstand a 400G impact, equivalent to being dropped from a second story window onto concrete. Each PackBot is also waterproof to 3 meters. Seven additional payload modules fit into the empty space above. Each module has power, Ethernet, serial, and USB connections to the PackBot for a fully flexible payload capacity.

PackBot is designed to be a robust platform for all-weather, all-terrain mobility. PackBot is at home in both wilderness and urban environments, outdoors and indoors. In the wilderness, PackBot can drive through fields and woods, over rocks, sand, and gravel, and through water and mud. In the city, PackBot can drive on asphalt and concrete, climb over curbs, and climb up and down stairs while carrying a payload. PackBot can also climb up, down, and across surfaces that are inclined up to 60 degrees. In addition, PackBot can climb up and down inclines of up to 55 degrees, and across inclines of 45 degrees, while carrying a 22.5 pound payload. Heavier payloads can be carried over less steep terrain.

PackBot is equipped with a sensor head that includes a color camera, a low-light black and white camera, a microphone, and a set of speakers. The sensor head provides real-time digital video (320 x 240 color images at 30Hz) and audio (12-bit resolution at 16 KHz). Alternative cameras such as an Indigo Alpha or Omega FLIR (forward-looking infrared) camera or a Sony FCB-EX780S zoom camera (25x optical zoom, 12x digital zoom, 300x combined zoom) can also be mounted in the sensor head. PackBot has been tested extensively and successfully at the Southwest Research Institute's mobile robot "torture track" in San Antonio, Texas.

PackBots are currently deployed in Afghanistan as part of Operation Enduring Freedom. Soldiers from the Army's 82<sup>nd</sup> and 101<sup>st</sup> Airborne Divisions and Special Operations have successfully used PackBots to explore cave complexes and suspected al Qaeda compounds. The PackBot operator control software has been integrated with the Exponent M7 wearable computer, allowing a soldier to control the robot using a portable joystick and a head-mounted

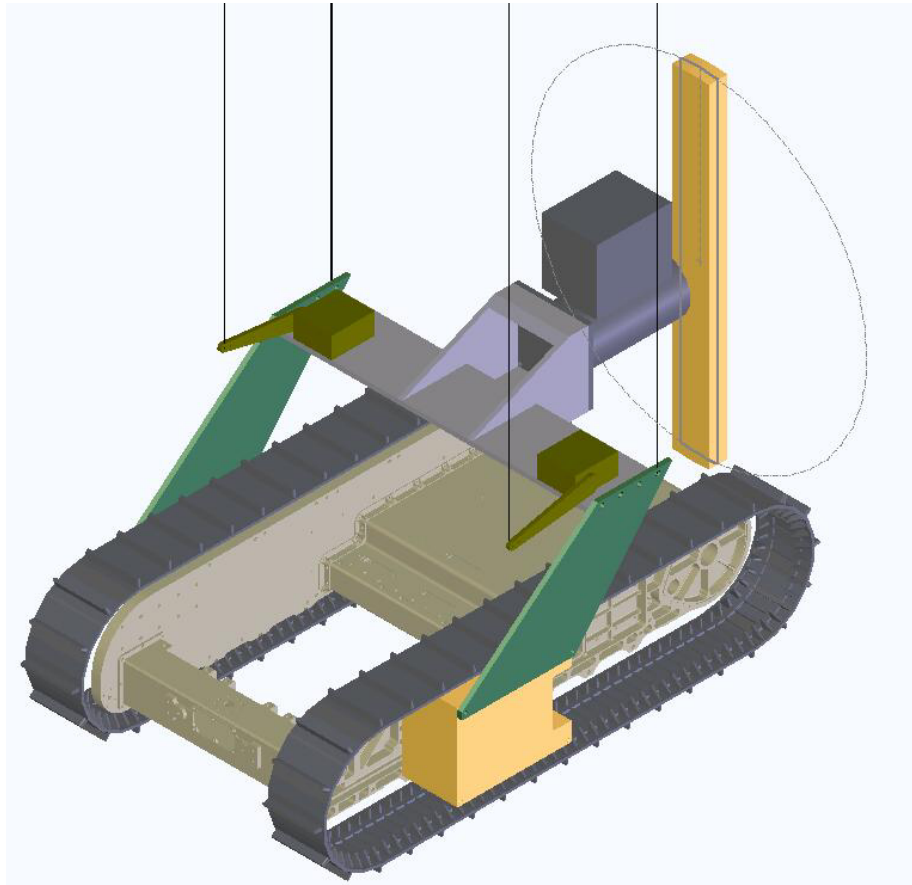
display. In July 2002, PackBots were used to clear 26 caves, four bunkers, three buildings, one compound, and one weapons cache. As front-line soldiers recognized the value of the PackBot, the Robot Team earned an official place as part of the Quick Reaction Force (QRF).



**Figure 1: PackBots search for hazardous chemicals in Iraq**

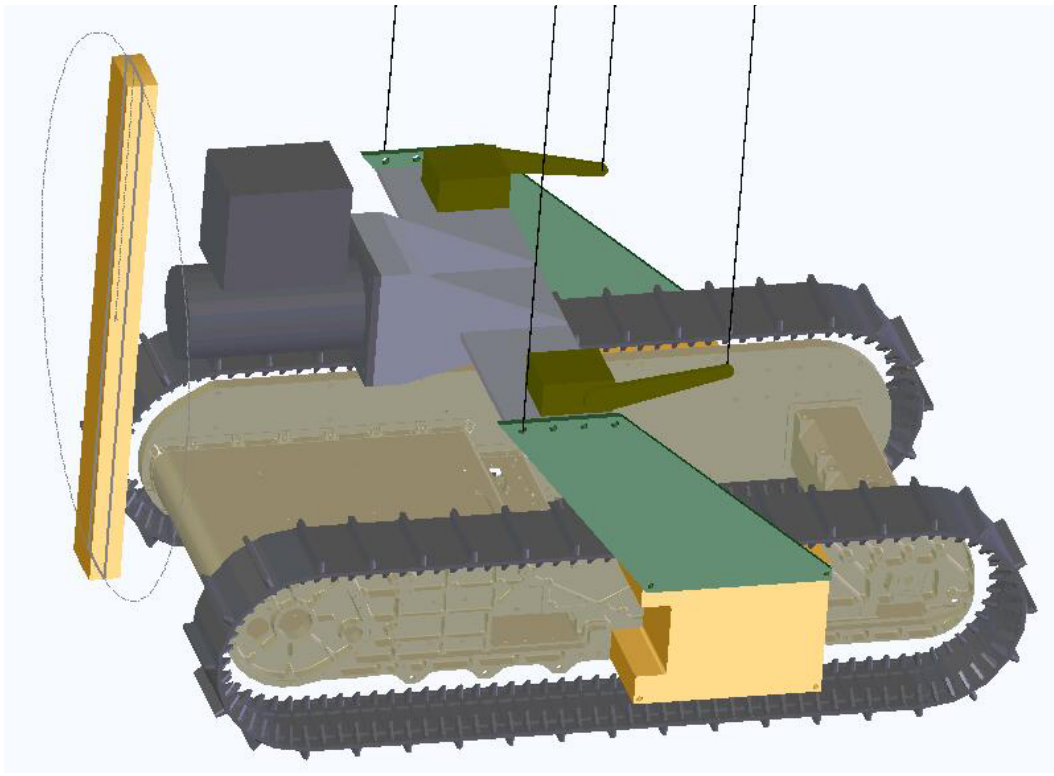
PackBots are also currently deployed with the 82<sup>nd</sup> and 101<sup>st</sup> Airborne Divisions in Iraq as part of Operation Iraqi Freedom. The 101<sup>st</sup> Airborne Division used a PackBot in the assault on Najaf. Army warfighters used the PackBot to perform room-by-room searches of the Najaf Agricultural Research Institute complex, which was suspected of housing Iraqi troops or Fedayeen guerillas. In addition, PackBots with chemical and radiation sensors have been deployed to Iraq, where they have been used to search mass grave sites for possible chemical contamination (Figure 1).

## AIR MOBILITY SYSTEM (AMS) OVERVIEW



**Figure 2: Griffon AMS Superstructure (vehicle facing away, propeller at front)**

The Griffon Air Mobility System (AMS) includes a superstructure that attaches above the PackBot and contains a platform on which is mounted a motor with a propeller at the front and two hang points for a parafoil on the sides (Figure 2). Two control arms in the back control the wing surface. The superstructure attaches to the rear side payload bays, which contain quick release mechanisms to jettison the AMS upon touchdown. A series of parafoil attach points is provided which will allow the operator to adjust for the center of mass fore and aft. The upper structure can be shifted to the left or right to adjust for small mass imbalances.



**Figure 3: Griffon AMS Superstructure (vehicle facing left)**

For the production Griffon, the standard PackBot Scout head (including color and low-light cameras) will fit in the forward payload area (Figure 3). This will provide real-time video for teleoperation during air and ground mobility modes, as well as visual reconnaissance information during autonomous flight.

We made the following assumptions in the Griffon design:

- Griffon will fly in horizontal position to make use of majority of existing camera payloads.
- The AMS will accommodate a range of CG locations, which can be adjusted by the launch operator before flight.
- The fore-aft range for CG will vary from 6 to 9 inches behind the torque tube.
- The side-to-side CG will vary by no more than 1 inch from centerline.
- The mass of the PackBot and all payloads with the exception of the AMS shall not exceed 55 pounds, nor be less than 40 pounds.
- The AMS is designed to be man-portable and to fit within a standard Pelican case such as the one used to transport the PackBot. The entire Griffon system, including PackBot, AMS, and OCU can be transported in two of these Pelican cases.

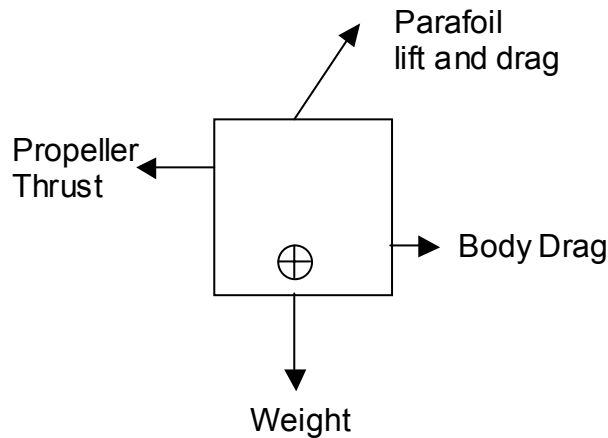
## FLIGHT SYSTEM CONFIGURATION

The AMS uses a parafoil for maximum compact storage volume. This provides a large wing area for slow take off and landing speeds. COTS parafoils are rare in this size. However, new extreme sports use traction kites similar to what we need, and can be made suitable with a

few modifications. These modifications involve re-trimming the wings default angle of flight and converting the kites to a four-control-line configuration.

Powered paragliders typically use a propeller in a pusher configuration. This is driven by two considerations: user comfort and efficiency. The user would be uncomfortable sitting directly in the prop wash, and a pusher propeller is more efficient in low speed vehicles since there are fewer obstructions to the prop wash. For our application, neither of these considerations applies. We use a puller prop configuration since for yaw stability reasons the propeller should be kept as close to the wing attach points as possible. Since the CG of the vehicle is biased toward the front, and the propeller must clear the vehicle, a forward prop is optimal.

## BALANCE OF FORCES



**Figure 4: AMS Force Diagram**

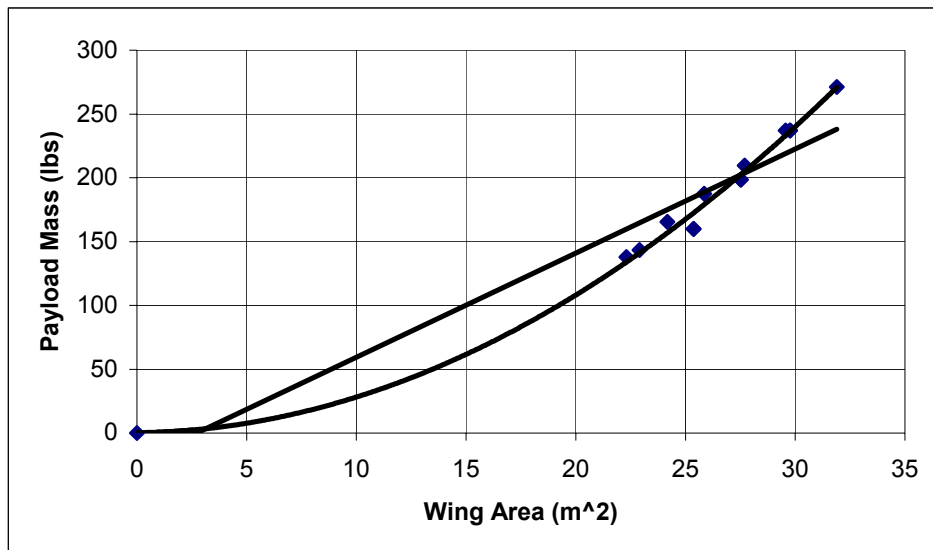
In the parafoil design, there is a substantial mismatch between the center of mass and the pro). Additionally, there is substantial mismatch between the thrust line and the center of drag (Cp). However, the low center of mass acts as a stabilizing pendulum, neutralizing these induced torques.

The hang point should be high on the AMS to maximize pendulum stabilization. The propeller thrust line should be slightly below the hang point, so as additional thrust is applied the propeller will cant upwards. At the same time, we want to minimize overall size to reduce drag. Torques will not balance in all cases, so the unit will not always be vertical, but a small pendulum displacement will cancel those torques.

## WING SELECTION

We performed quantitative analyses of paraglider wing loading scaled to the weight and speed required for a PackBot-based Griffon UAV/UGV. We conducted these analyses assuming an initial weight estimate for a PackBot-based Griffon UAV/UGV of 55 pounds (25 kg)

(including AMS) and an estimated Griffon launch speed of 12 mph (5.4 m/sec). The results of these analyses indicated a minimum wing area of 10 to 16 square meters for the AMS parafoil.



**Figure 5: Wing Area vs. Payload Mass for COTS Paragliders**

We can use either linear or quadratic extrapolation to estimate the necessary wing area (Figure 5). Since aerodynamic forces are related to the square of the velocity, the quadratic extrapolation is more valid. However, we are shooting for a slower airspeed than is typical for a paraglider, which is generally trimmed for 25 mph.

We then conducted a trade study of COTS paragliders that would be suitable for the Griffon prototype flight tests. As part of this trade study, our aeronautical lead initiated consultations with several internationally-known experts in parafoil design, including Kouki Kazanaka of Viokite and Kinsley Wong of Extreme Big Air, both of whom have extensive experience in the design, development, and production of commercial paragliders.

In this range there are two types of wings available: kite surfing wings and traction wings for extreme sports. Current kite surfing technology uses a preinflated wing, where the inflated bladder gives the wing structural shape and provides for floatation in water. The kite surfing wings have a fixed trim angle, provided by the integral inflated structure. In contrast, traction wings, used for carts, snowboards, and sleds use more traditional ram air inflation. This allows for a more compact stowed size, and allows the wing to be retrimmed for a suitable angle of attack. For this reason, ram air inflated traction wings were selected for the Griffon AMS prototype.

Four potential wing choices were examined: the Frenzy, Little Devil, and Razor kites manufactured by Ozone, and the Alpina kite manufactured by F-One. After comparing the parameters of each wing, we determined the Ozone Frenzy and Ozone Razor were best suited for use as the AMS parafoil. We acquired a 9 m<sup>2</sup> Ozone Frenzy and an 11 m<sup>2</sup> Ozone Razor for use in the flight tests.



## ENGINE AND PROPELLER SELECTION

We estimated the power range needed from the engine based on system mass and desired flight characteristics:

$$\text{Power} = \text{Drag} \times \text{Velocity}$$

We estimate worst case drag to be the system weight, so for a 60 pound system with a maximum speed of 15 mph, we would need slightly over 2 BHP. This is modified by propeller efficiency and parasitic prop wash losses but provides us with a rough approximation. We confirmed this power range based upon extrapolation from existing commercial powered paraglider units.

We considered several engines in this power range, and we selected the BT-32A engine manufactured by Fuji Engines for the Griffon prototype. This 32cc engine provides 2.2 HP of power and weighs 3.7 pounds. We attached this engine to a standard 18x8 propeller and integrated it with the prototype AMS.

## AMS SUPERSTRUCTURE

We designed the AMS superstructure to be as aerodynamic as possible to minimize parasitic drag. This is not as critical for the rest of the vehicle since the flight speeds are so low. However, the airspeed of the propwash is very high, so parasitic drag can drastically reduce the effective thrust of the propeller if the structure is not carefully designed.

We chose to use aerodynamically-faired extruded aluminum tubing, sold by Aircraft Spruce, for the main structural components that are in the propwash. The electrical harness to the control servos was routed through the inside of this tube. The harness was then connected to sockets on either end of the tube, near where the side plates attach.

Using solid aluminum inserts, the structure was bolted together with stainless 10-32 hardware, using appropriate anti-vibration adhesives. The side plates were made from thick plate aluminum for simplicity of manufacture. In a future revision, these structures could also be made of streamlined tubing with mounting points for the control servos. An advantage of the streamline tubing over the plate style construction is that the electrical harness can be routed through the inside of the tube to the PackBot.

With simple flat aluminum plate on the sides, there was a substantial amount of vibration in the structure while the motor was running. We considered adding stabilizing cross cables, but decided the vibrations were not large enough to justify the additional drag, cost, mass, and complexity.

We also considered welded aluminum tubing, but this would not allow for quick assembly from a small compactly stowed configuration. That is, it would be hard to fit a welded aluminum structure inside a standard PackBot Pelican shipping case.

## CONTROL MECHANISM

For the Griffon prototype, we have adapted COTS radio-control components, typically used for R/C aircraft, to control our proof-of-concept demonstrator. We use one Futaba S3004 general purpose servo to control the engine throttle and another to actuate an engine kill switch.

We used a Futaba FP-R138DP RCM 1024 to receive R/C signals from a Futaba 6XA Super PCM 72.910MHz (channel 56) R/C transmitter. The receiver includes programmable responses to communications loss to facilitate safe recovery of the vehicle during testing. We used an identical transmitter and receiver to control the PackBot Alpha 2 prototype, but on a different frequency (75.570MHz, channel 69).

The control mechanism for steering and controlling the pitch of the parafoil went through four generations of design. This mechanism controls the parafoil by tugging on two toggle lines, which are attached to the rear of the parafoil on both the left and right trailing edges.

The first generation design consisted of simply tying the toggle lines to the ends of 5 inch servo arms attached to two Hitec HS715BB sail-arm servos. This provided an inadequate range of control for some kites, and the protruding arms were rather fragile.

The second generation design extended the throw of the original arm servo using a four-bar linkage system. While this provided twice the control range, the torque output was insufficient. The design was also rather fragile to collisions and general rough handling, and parafoil lines would tend to snag on mechanism fasteners during ground handling.

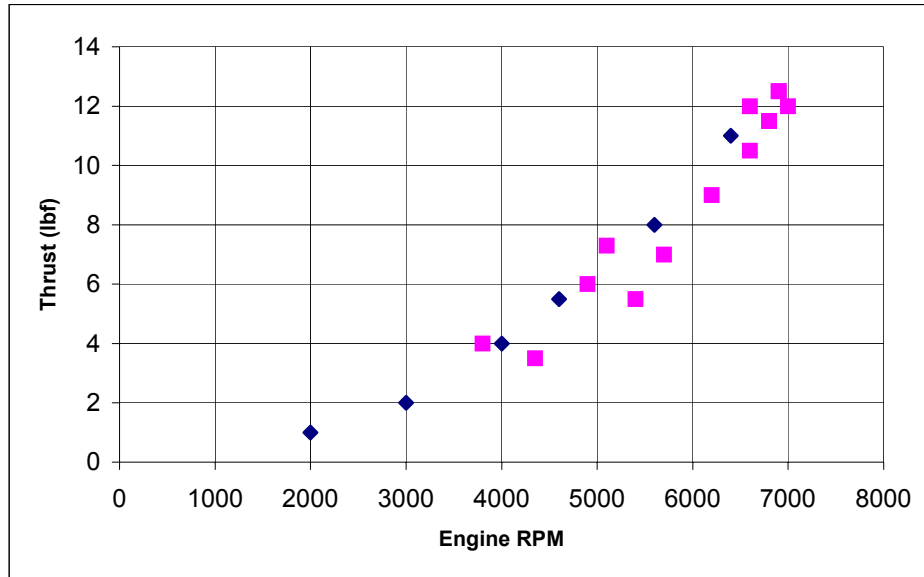
The third generation attempted to correct all these issues by doing away with the control arms by using a spool mechanism. Since line tension cannot be assured during all operations, the spool mechanism operated with monofilament, so that the mechanism could unspool even when there is no tension. This first design proved too fragile, and the spool did not provide sufficient number of rotations to provide the control authority desired.

The fourth, and final, design used higher performance Futaba S5801 sail winch servos, with a more robust spool cover. This provided plenty of range for all operations and had power to spare. The mechanism was protected by weak links that attached the monofilament to the parafoil kite lines. These links were designed to break before the servos if the parafoil became caught on an obstruction during takeoff runs. A small elastic section was added at the end of the monofilament to reduce shock loading from possible snags and to give the weak link time to break.

## GROUND TESTS

We developed a wooden PackBot mock-up payload for use in initial ground tests and early flight tests. This mock-up was the general size and shape of a PackBot and was supported on free-rolling wheels.

Using the PackBot mock-up, we extracted engine performance data. By varying the throttle settings, we recorded the total system thrust at different engine speeds (Figure 6). These results confirmed our assumption that the Fuji BT-32A would have sufficient thrust to power the Griffon Prototype.



**Figure 6: Thrust vs. RPM for Fuji BT-32A**

Next, we attached the PackBot mock-up to the AMS prototype and hung the system from a fixed stand as if it were attached to a wing. During these tests we encountered some roll-yaw instability. We attempted several methods of stabilization, such as changing the roll-yaw moment of inertia, adding a vertical tail stabilizer, and shifting the location of the center of mass relative to the propeller disk. The results of these efforts convinced us that this stability was an artifact of the test set up, and this was verified in later test flights.

### FLIGHT TESTS WITH MOCK-UP PAYLOAD

In May 2003, we began initial flight tests with the Griffon Phase I Prototype. These tests were performed at Camp San Luis in San Luis Obispo, with the cooperation of the California National Guard.

In the first set of tests, we attached the Griffon AMS to the wooden PackBot mock-up payload. This mock-up is designed to simulate the size, weight, and shape of the PackBot, and includes passive free-rolling wheels. The total weight of this system was approximately 45 pounds.

We launched the Griffon prototype under power of the AMS gasoline engine alone. The AMS engine was sufficiently powerful to accelerate the prototype to takeoff speed. On takeoff, the Ozone Razor parafoil inflated and provided the necessary lift to launch the prototype into the air. On the first flight, the prototype flew to an altitude of approximately 50 feet above the ground for a distance of about 300 feet. We then brought the vehicle down for a soft landing in tall grass.

We encountered some difficulty in controlling the prototype's motion on the ground using the AMS engine with the passive mock-up payload, due to the inability to steer the mock-up wheels. This issue was addressed in later flights by the active control provided by the powered treads of the radio-controlled PackBot prototype.

## FLIGHT TESTS WITH PACKBOT PROTOTYPES

Following the successful tests with the mock-up payload, we replaced the wooden mock-up with an actual radio-controlled PackBot Alpha 2 prototype. This PackBot prototype was capable of ground speeds of up to 4 meters per second. PackBot's flippers helped to stabilize the vehicle by automatically inducing a turn towards the wing when the vehicle is lifted on edge.

The PackBot prototype was equipped with a Futaba FP-R138DP PCM 1024 receiver, identical to the one used for the AMS, but set for a different frequency (75.570MHz for the PackBot, 72.910MHz for the AMS). We used identical Futaba 6XA transmitters to control both the PackBot and the AMS.

The previous Griffon AMS package was modified with new spooler servo mechanisms to control the parafoil toggle lines. This spooler was mounted lower on the side plates to allow the insertion of an elastic section in the toggle length, and to allow full retraction of the toggle lines. The spooler is both more powerful and faster in response.

On June 11<sup>th</sup>, we conducted the flight demonstration for this project. In this demo, we tested the complete Griffon Prototype, consisting of the PackBot Alpha 2 with flippers and the Griffon AMS. The total weight of this system was 58 pounds.

We first performed several inflation runs using a new 11m Razor parafoil. These tests were successful. We then launched the complete Griffon prototype on its first flight. Wind conditions were calm. During these tests, one operator controlled the PackBot UGV and another controlled the Griffon AMS and parafoil. Initial parafoil inflation was slightly uneven, but quickly leveled out, and we opened the throttle on the AMS.

We executed a takeoff in a shallow climb, with more "brake" needed than expected to maintain climb. The flight was very stable and easily controlled. We initiated a slow right turn and followed the fence line on the north side of the airstrip when we unexpectedly encountered a tree. The pilot in command mistakenly assumed all the trees were outside the fence line. Total flight time was 34 seconds. Frame by frame analysis of the video indicates the impact speed with the tree was approximately 21 mph.

With the assistance of the National Guard, we recovered the PackBot and the AMS from the tree undamaged. However, the parafoil was destroyed in this process. Fortunately, we had the old 11m Razor parafoil, whose lines had been slightly damaged in a previous flight test. We attached this parafoil to the Griffon prototype and conducted a second test flight.

However, due to the line damage, the parafoil shape was slightly unbalanced. When doing inflation runs without the AMS engine active, the left wingtip would always lift first, and it would take substantial control to correct until the parafoil was over the vehicle. As a result the vehicle was somewhat unstable, with substantial roll oscillations that would grow without active pilot input. Pilot input could successfully damp the oscillations, but at the risk of aggravating pitch oscillations. When pitch oscillations were outside the level of control of the pilot the engine was killed and the vehicle landed on the grass. Total flight time was 51 seconds.

We concluded that the instability was due to the fact that the damaged lines were slightly shorter than the other lines, resulting in an asymmetrical parafoil shape. To solve this problem, we adjusted the parafoil line lengths to return to the original balanced shape.

We then launched the Griffon on its third and most successful flight. Winds had increased to approximately 6 mph. During the launch, the headwinds were sufficient to pull the PackBot backwards a bit during the inflation.

With the parafoil repaired, the Griffon once again flew in a stable and easily-controlled manner. After launch, the pilot made a gentle right turn around the edge of the airfield, carefully avoiding the tree. We then ascended to an altitude of 150-200 feet and performed a complete circuit of the airfield.

Finally, we turned back over the runway and reduced the throttle, coming in to land at the end of the runway away from personnel and vehicles. Just before landing there were some pitch oscillations. Before touching down, we activated the PackBot's tracks so the vehicle hit the ground running and made a smooth transition from flight to ground motion. Total flight time was 89 seconds.



**Figure 7: Griffon takes off**



**Figure 8: Griffon flies over airfield**



**Figure 9: Griffon in flight**





**Figure 10: Close up of PackBot and Griffon AMS in flight**



**Figure 11: Griffon comes in for landing**

## CONCLUSIONS

Our successful flight tests demonstrated that the Griffon concept is sound, and validated the following assumptions of this project:

- An 11m Razor parafoil can provide sufficient lift to launch the PackBot and AMS into the air and ascend to a desired cruising altitude.
- A 32cc, 2.2 HP gasoline engine can provide sufficient thrust for takeoff and for controlled flight in mild wind conditions.
- A two-channel servo control system attached to the parafoil control lines is sufficient to provide control of vehicle heading during flight.
- AMS engine and parafoil control can be coordinated with PackBot UGV tread control to provide smooth takeoffs and landings.
- The use of a parafoil wing limits use of this vehicle to relative calm weather conditions (less than 10 mph wind velocity).

While Phase II of this SBIR was not funded by TACOM-ARDEC, the Griffon project has advanced to the point where it could be transitioned into a fully-operational prototype with appropriate funding. The complete Griffon vehicle would support teleoperated UAV/UGV control including real-time video, autonomous flight navigation capability using GPS waypoints, and semi-autonomous launch and landing capabilities. In addition, the use of a lightweight fixed wing, similar to that used by hang gliders, could also be investigated to extend the range of weather conditions in which this vehicle could be used.

## ACKNOWLEDGMENTS

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### **Dr. Brian Yamauchi, Principal Investigator**

Dr. Yamauchi is a lead roboticist at iRobot Corporation and the Principal Investigator on the Wayfarer Project funded by the U.S. Army Tank-automotive and Armaments Command (TACOM) Tank-Automotive Research, Development, and Engineering Center (TARDEC). Wayfarer's goal is to develop a navigation system that will enable PackBots to conduct autonomous reconnaissance missions in urban terrain. He is also Principal Investigator on the Sentinel Project, an SBIR project funded by TARDEC to investigate semi-autonomous command



and control systems for multirobot teams. In addition, he is the Principal Investigator on a project funded by the U.S. Army Telemedicine and Advanced Technology Research Center (TATRC) to develop a PackBot payload that can be used to rescue casualties from the battlefield. Previously, as part of the DARPA-funded Deployer project, he developed software for distributed mapping and navigation using heterogeneous robot swarms.

Prior to joining iRobot, Dr. Yamauchi conducted research at the Naval Research Laboratory, where he developed frontier-based exploration, a technique that enables mobile robots to explore and map unknown environments. As a member of the technical staff at NASA's Jet Propulsion Laboratory, he developed a behavior-based navigation system that enabled Rocky III, a six-wheeled Mars rover prototype, to navigate across unknown terrain. Later versions of the Rocky rovers were used as prototypes for the Sojourner rover used in the Mars Pathfinder mission. He has also conducted robotics research and development at NASA's Kennedy Space Center, Hughes Research Laboratories, and the Institute for the Study of Learning and Expertise.

Dr. Yamauchi received a B.S. in Applied Mathematics/Computer Science from Carnegie Mellon University, an M.S. in Computer Science from the University of Rochester, and a Ph.D. in Computer Science from Case Western Reserve University.

## **Pavlo Rudakevych, Mechanical Lead**

Mr. Rudakevych is a Principal Research Engineer at iRobot Corporation and has led numerous research projects in a variety of technical areas including: the control of tentacled robots, design of kilogram class outdoor mobility systems, using vision systems to guide robots, and the design of safe systems for remote weapon activation. He previously worked at Hughes Space and Communications as Spacecraft Mission Lead for PanAmSat 4, which provides video, telecommunications, and Internet services for Europe, Asia, Africa, and the Middle East.

Mr. Rudakevych holds a B.S. in Aerospace Engineering from MIT and an M.S. in Aerospace Engineering from USC. He is also licensed as a professional mechanical engineer and is an advanced rated paraglider pilot.